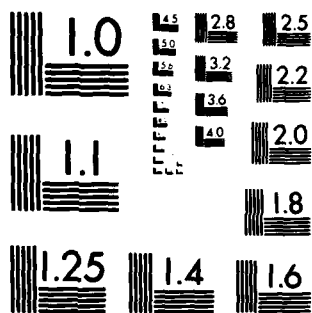END
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Final Report
for the period
9 January 1984 to
15 April 1984

Solar Thermal Propulsion: An Investigation of Solar Radiation Absorption in a Working Fluid

June 1984

Author:
Frank J. Perry

Approved for Public Release

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**Air Force
Rocket Propulsion
Laboratory**

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FOREWORD

This project was performed in-house at the Air Force Rocket Propulsion Laboratory, Edwards Air Force Base, California 93523 under JON: 2308M3RX. Frank Mead and Curt Selph served as Project Managers.
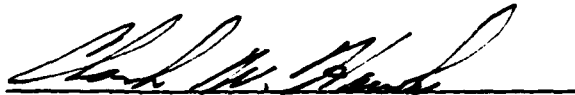
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CURTIS C. SELPH
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Chief, Advanced Propulsion Br.

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The objective of this solar thermal propulsion study was to examine the state of the science of direct absorption of solar radiation into a working fluid for use in propulsive devices. In particular, the absorption characterisitics of alkali seeded hydrogen gas were investigated. Because of obvious parallels, the laser propulsion literature was reviewed as well as the solar propulsion literature. The investigation also covered peripheral areas such as aerodynamic windows and alkali/hydrogen mixing techniques. This report presents the important details from the existing information with an extensive list of references included. Recommendations for future theoretical and experimental Air Force research were made based upon the data uncovered.

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LIST OF ILLUSTRATIONS

1.0 INTRODUCTION

This report is the result of an in-house research effort sponsored by the Air Force Office of Scientific Research. The objective of this study is to plan a comprehensive research effort in solar thermal propulsion based on direct volumetric absorption of sunlight that takes advantage of the existing Air Force Rocket Propulsion Laboratory (AFRPL) solar facilities. This report presents such a plan, both theoretical and experimental, that is based on an extensive literature search in the beamed energy propulsion area. Because of certain parallels, the survey included laser propulsion literature as well as prior solar propulsion studies.

With the Air Force's increased interest in orbit transfer vehicles, there is a need for moderate thrust, high performance propulsion units. A solar thermal propulsion device can meet these requirements. Conventional chemical engines are high thrust vehicles with low specific impulse (Isp) (200 - 500s). Electric propulsion offers high Isp (1,500 - 3,000s) but relatively low thrust (fractions of a pound). A solar thermal propulsion device falls between these bounds. A solar thruster can provide relatively moderate thrust levels (tens of pounds) while maintaining good performance (800 - 1,200s).

The concept of a direct absorption, solar thermal propulsion unit as discussed in this report uses concentrated solar energy to heat a working fluid to the plasma state which is then accelerated through a nozzle to create thrust. Incident solar radiation is admitted through a window and is absorbed in a central region called an absorption zone. The working fluid, in this case hydrogen gas seeded with alkali metal vapor, enters the upstream portion of the absorption chamber and flows uniformly through the focal point where it absorbs the energy. The fluid is then exhausted through a nozzle.

Hydrogen gas is selected as the primary working fluid because of its low molecular weight. Low molecular weight enhances performance since the specific impulse is directly proportional to temperature and inversely proportional to molecular weight ($Isp \propto \sqrt{T/M}$). Because hydrogen is almost transparent to solar radiation, the alkali seed, although it increases molecular weight and lowers performance, is necessary to efficiently absorb

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the solar radiation and to transfer it to the hydrogen working fluid. The alkali metals have broad band absorptions and low ionization potentials. The alkali atoms will become electronically excited and some photoionization will occur and at the same time rotational and vibrational modes will be excited in dimers. The hydrogen will absorb energy and relax these excited states through collisions. The overall effect is to produce a uniform, very high temperature working fluid for expansion through a nozzle.

This concept where the energy is absorbed into the working fluid without the use of a heat exchanger device is called a direct absorption method. This approach has several advantages over other concepts such as the AFRPL solar thruster[1] and solar fixed bed.[2] The AFRPL solar thruster is a heat exchanger thruster. Sunlight is focused on rhenium coils which heat and transfer the absorbed energy to hydrogen gas flowing inside the coils. The solar fixed bed thruster is similar to nuclear fixed bed reactor concepts.[3,4] The performance of the "indirect absorbers" is limited by material properties such as melting point and structural strength. The state-of-the-art operating temperature for an indirect absorber is currently approximately 2700°K due to high temperature creep and loss of strength of the rhenium. There is a considerable difference in performance between the two conceptual approaches since the theoretical temperature that can be reached using solar energy is approximately 5,600°K, the surface temperature of the sun, assuming perfect absorption and no losses. Direct absorbers are not limited nearly as much by material properties, therefore, higher temperatures (2,700°K < T < 5,600°K) and thus achieve higher performance. However, direct absorption is newer and less well understood, therefore, technology in this area must be advanced before the full potential of the solar plasma thruster can be realized.

2.0 REVIEW OF PREVIOUS RESEARCH

There are many physical processes and phenomena that occur in a beamed energy propulsion device. For a solar thermal propulsion unit one must consider the properties of solar radiation, how it can be concentrated, and how the light interacts with the working fluid. Because the heated working fluid will be expanded to generate thrust where performance is proportional to temperature, accurate analysis of absorption is the key element to a successful design of a solar thermal thruster. Inclusion of the radiation absorption mechanisms in the theoretical models and experimental characterization in addition to the usual thermodynamic, fluid dynamic, and heat transfer processes that occur in conventional propulsion systems is the focus of attention for this report.

Over the years the majority of the beamed energy propulsion research that has been done has focused on laser energy absorption. Many concepts that have been proposed use either of two component systems: thruster and radiation source. In these systems the laser is either ground-based or space-based. Focusing and tracking are much more difficult to do from the ground than in space. High power space-based systems are more difficult to operate in that they are not as easily accessible and they are more expensive than ground-based systems.

The inherent difficulties of laser propulsion have aroused interest in solar radiation as an energy source for propulsion. The major advantage of using solar energy is that a man made radiation source is not needed. Solar radiation is free and available, for the most part, at all times. However, solar radiation is a dilute form of energy and requires larger concentrators to collect the energy. The inconvenience of supplying the required concentrator for a solar propulsion system is thought to be less disadvantageous than supplying a laser radiation source for a laser propulsion system.

2.1 Laser Research Summary

With the availability of laser propulsion research, it is beneficial to
become familiar with working concepts that could be applied to the solar
concept being considered. A detailed review of the significant laser
theoretical and experimental research is presented in the Appendix. The more
noteworthy items and essential pieces of information from the laser research
are presented below. Previous solar research is discussed in Section 2.2.
Keep in mind that the specific results (ie, measured or calculated parameters)
are not as important as the success of the theoretical models, experimental
techniques, and the diagnostics used.

It is important to be able to understand and predict the physics involved
in a flowing solar sustained plasma. It is not known whether combustion and
detonation waves or large "fireballs" will occur as a result of solar
radiation absorption. Models coupling solar radiation to a flowing gas are
rare. The majority of the theoretical models have been developed for laser
plasmas. Laser supported combustion waves (LSCW) are used as the basis for
theoretical analyses of laser sustained plasmas. This technique is examined
for application in analyses of solar sustained plasmas.

The first analysis of coupling laser energy to a flowing gas was
accomplished by Raizer[5]. He developed the mass momentum, and energy
conservation equations for the flow through a LSCW. Kemp and Root[6] expanded
Raizer's work to include realistic property variations. Like Raizer, Kemp and
Root assumed the pressure throughout the LSCW to be constant which reduced the
equations of motion to a single ordinary differential equation. The equation
is basically a 1-D energy balance with the mass flux as an eigensolution. The
formula is written as

$$\frac{d}{dx}(\text{ uH}) + \frac{dI}{dx} + \frac{dSA}{dx} + P_T = \frac{d}{dx}(\lambda c \frac{dT}{dx}),$$

where: $\frac{d}{dx}(\rho uH)$ = convection,

$\frac{dI}{dx}$ = absorption,

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$$\frac{dSA}{dx} = \text{radiation energy transport,}$$

$$P_T = \text{radiation loss,}$$

$$\frac{d}{dx} (\lambda \ c \ \frac{dT}{dx}) = \text{thermal conduction;}$$

$T = $ temperature,

$\lambda = $ gas density,

$u = $ gas velocity,

$H = $ gas enthalpy,

$I = $ laser intensity,

$S_A = $ radiation energy,

$P_T = $ radiation loss,

$\lambda_c = $ thermal conductivity, and

$dx = $ incremental axial distance.

The above equation is a second order one-dimensional differential equation for the axial temperature profile, T(x), of an LSC wave. The equation is written in wave-fixed coordinates. Kemp and Root have expanded this work to include some 2-D effects such as pressure and area changes to simulate nozzle streamtub flow, radial conductive losses, and beam convergence.

Keefer has also modeled the laser supported plasma.[7] His analysis is very similar to Kemp and Root but written in two-dimensional form. Approximations of the energy absorbed and the assumption of constant coefficients allowed the equation to be reduced to basically one dimension with temperature as the only two-dimensional variable. To date, this analysis has produced the only two-dimensional temperature profile of an LSC wave.

Merkle, recently, has formulated the radiation-gas dynamic interaction using complete Navier-Stokes equations.[8] This represents a solution where incompressible and inviscid flow is not assumed. Although this solution would possibly be more accurate, nonlinearities and problems with the implicit time-matching procedure caused the solution to diverge in some regimes. A complete understanding of LSCW flow still has not been presented.

At present, there is insufficient experimental evidence to support or disprove the theoretical formulations. The basic fluid dynamic, thermodynamic, and heat transfer equations from these models may be used as a foundation to begin an analysis of "solar supported combustion waves" (SSCW) which is analogous to LSCW flow. From the theoretical research,[6-8] there are some general features of combustion waves that deserve mention. These properties are typical of combustion waves whether they are solar or laser supported. They are:

o   Intensity of a beam specifies unique mass flux,

o   Temperature profiles rise sharply, have a peak in which the width is relative to the total thickness, and then fall gradually,

o   The higher the beam intensity, the higher the maximum temperature, almost independent of pressure,

o   Pressure strongly affects the thickness of the wave with the absorption coefficient being pressure dependent.

o   The greater the pressure, the thinner the wave becomes, and

o   Pressure effect on mass flux is not large at any given intensity.

It was stated that there has been insufficient experimental research to support or disprove theoretical models; however, there are some experimental studies that have made significant contributions to the field of beamed energy propulsion. This experimental laser research presented is of interest because the experimental techniques and diagnostics used can be applied to solar thermal propulsion. The more important points are discussed herein and the Appendix contains a detailed description of the experiments.

United Technologies Research Center (UTRC) performed experiments to measure temperature dependent absorption lengths of hydrogen-water mixtures at high temperatures and pressures using a high power CW CO_2 laser (10.6 μm).[9] A high pressure gas cell was used for containment. Laser probes were used to determine the spatial dependence of power loss and optical phase shift of 10.6μm light as it passed through the gas. The absorption, ΔP, could then be calculated from this information.

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$$\Delta P = \ln(I_r/I_c) + \ln(I^o_c/I^o_r),$$

where:

I_r = reference intensity,

I_c = cell intensity, and

Superscript:

^{o} = values obtained prior to establishment of the plasma.

In this work, breakdown occurred easily and no difficulties in sustaining a plasma were encountered as long as the initial cell temperatures were near ambient. Large window refractive index gradients from large temperature gradients due to high cell temperatures (>> ambient) caused focusing problems; therefore, the plasma would extinguish. Measured absorption was found to be much higher than predicted; therefore, work continued.

PSI also performed absorption measurements on the same mixture.[10] In a shock tube experiment, hydrogen was used as a driver gas with an argon-water vapor as the driven gas. This approach was used to almost instantaneously take the gas mixture to a desired temperature. The laser absorption tests were then made at these high temperatures (significant absorption will not occur at low temperatures, < 1,000°K, for Ar/H_2O mixtures). Laser probes were used to determine the optical path length, 1, and the transmission, I/I_o. Knowing the initial mole fraction of water, X_{H_2O}, the total pressure P, and the equilibrium temperature fractional dissociation f_T, the absorption coefficient α , could then be calculated.

$$\alpha = (\ln I_o/I)/f_T \, X_{H_2O} \, P$$

The results were shown to be characteristic of a fully pressure-broadened gas, and therefore were transferable to H_2/H_2O mixtures. The absorption coefficients were much lower than the UTRC results, and in better agreement with theoretical predictions. In a more recent program, NASA Marshall and the AFRPL have started another experimental program to measure laser absorption in water vapor." A thermal absorption wave is used to generate temperatures suitable for absorption measurements. Laser heating of a ceramic endwall causes local gas heating which develops into a thermal wave. Acoustic

and spectral measurements will be made to determine temperature and absorption. Spiricon detectors, a HeNe probe laser, an eximer laser, and a McPherson spectrometer will be used for these measurements. This work is incomplete but results are soon to follow.

Perhaps more notable laser research was accomplished by AVCO Everett Research Labs (AERL).[12] The purpose was to evaluate laser absorption in a flowing gas with thruster configurations. In this case, a laser thruster was actually designed, fabricated, and tested. A hydrogen-cesium mixture was chosen as the propellant with inverse Brehmsstrahlung as the primary absorption mechanism. Diagnostics were not extensive. Breakdown and plasma ignition occurred with reproducibility. The most important result of this research is that the laser thruster concept was proven.

The laser research presented here is important because it can be applied to solar absorption research. Temperature measurement and absorption calculation techniques that have been successful in laser research can also be used in solar reserach. Understanding the advantages and disadvantages in the different designs of experimental apparatus is helpful in successfully designing solar experimental research equipment.

2.2 Solar Research

2.2.1 <u>Absorption of Solar Radiation by a Hydrogen-Alkali Mixture</u> - The direct absorption process is the key element to a solar thermal propulsion device. The size of the thruster must be scaled with the absorption lengths of the propellants. Because of cost and weight constraints, it is necessary to keep the absorption length as small as possible.

Because hydrogen is essentially transparent to sunlight at temperatures below 8,000°K, it is advantageous to seed the hydrogen with a material that will ionize and absorb at low temperatures (T << 5,600°K). Alkali metals are good seedants because they have low ionization potentials. Inverse Brehmsstrahlung absorption cannot occur without free electrons present, therefore ionization and hence a low ionization potential is important. More importantly, photoionization and photo-detachment are processes that occur

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more readily when low ionization potential seedants are used. Photoionization is the main absorption mechanism at visible wavelengths. Very energetic light (ultra-violet frequencies) would be needed to produce ionization if the ionization potential is too large. This is not desired since the ultra-violet flux in solar radiation is small.

The alkali will be present in different states in the hydrogen–alkali mixture (alkali atom abbreviated ALK):

ALK   alkali atom,

ALK +   alkali positive ion,

ALK −   alkali negative ion,

ALK_2 alkali dimer.

There is a variety of alkali absorption processes that will occur:

$ALK + h\nu$ -- $ALK*$, electronic state transition (bound–bound);

$ALK + h\nu$ -- $ALK^+ + e^-$, photoionization (bound-free);

$ALK^- + h\nu$ -- $ALK^+ \, ALK + e^-$, excited state photoionization (bound-free);

$ALK_2 + h\nu$ -- ALK_2^*, dimer excitation (rotational + vibrational);

$ALK, ALK^- + e^- + h$ -- $ALK, ALK^- + e^{-}*$ -- $ALK*, ALK^-* + e^-$;

      inverse Brehmsstrahlung (free-free).

(Superscript* = excited state)

($h\nu$ = photon energy)

The production of free electrons is necessary for inverse Brehmsstrahlung absorption. This is important since in the infrared wavelengths these mixtures will primarily absorb via the inverse Brehmsstrahlung absorption process.

The absorbed energy of the alkali is transferred to the hydrogen by collisional quenching and relaxation. The overall effect is to increase the average thermal energy of the working fluid. This is represented by the equations below:

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$ALK^* + H_2 \rightarrow ALK + H_2^* + \Delta E$, collisional quenching of alkali atoms by diatomic hydrogen;

$ALK_2^* + H_2 \rightarrow 2ALK$, $ALK_2 + H_2^* + \Delta E$, relaxation of alkali molecules by diotomic hydrogen;

$H_2^* + H_2 \rightarrow 2H_2 + \Delta E$, relaxation of excited hydrogen.
(ΔE = thermal energy increase)

These collisional transfer and relaxation processes occur very rapidly. As long as the temperature and pressure are not too low, the energy transfer rate to the hydrogen can be considered instantaneous with the working fluid remaining in thermodynamic equilibrium.

A continuous absorption coefficient is neccessary to describe solar radiation absorption. The continuous absorption coefficient is derived by computing the atomic cross section (probability) for each absorption mechanism that will occur across the spectrum for the given absorber. These cross-sections are then converted to absorption coefficients for each process which are then superimposed to form a continuum. Figure 1 is a continuous absorption profile for potassium.

Recently, with the realization of the application of the alkali metals because of their low ionization potential and "benchmark quality", experimental research to determine the continuous absorption coefficient of the alkali metals has started. Previous research was almost negligible. There has been, however, a greater amount of theoretical work. Many studies have been done, each employing different calculation techniques with the results more mutually consistent than with experimental values. Most of the available experimental data can be found in References 13 - 16, 25.

The continuous absorption coefficient, as shown in Figure 1, has been pieced together from References 17 - 22 by Mattick.[23] Similar theoretical information is also available for other alkali metals.[17-22] It is therefore possible to obtain continuous absorption profiles for cesium, sodium, lithium, and rubidium. This information will be useful for seedant selection and performance prediction.
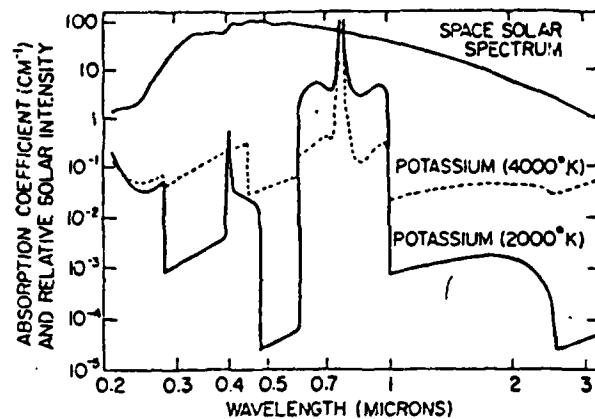
Transition	Wavelength, μm	Temperature, K
4s photoionization	< 0.28	all
4p photoionization	< 0.45	> 2000
Dimer X-C, atomic 4s-5p	0.4-0.47	< 4000
3d photoionization	< 0.74	> 2500
Dimer X-A, X-B, atomic 4s-4p	0.6-1.0	all ?
K⁻ photoionization	0.6-2.4	> 2000
K,K⁺ inverse Brehmsstrahlung	> 2	> 2500

Figure 1. _Continuous Absorption Coefficient for Potassium with Occurring Transitions._ (Ref. 23)

2.2.2 <u>Prediction Model Capability</u> - To date, there are no models that describe the interaction of solar radiation with an alkali seeded hydrogen gas. The most useful model discovered considers solar radiation absorption of an alkali vapor. This model, which appears to be very complete, has been developed by Hughes Research Laboratories.[24] The model contains a total energy balance which includes radiation losses, thermal conduction, convection, cesium absorption, and gas flow. The model is not well documented but the basic assumptions are known. The model assumes local thermodynamic equilibrium exists with electron and heavy particle temperatures being equal. Reabsorption of reradiation is neglected. The plasma temperature is assumed to be independent of the position in the plasma for the static case (no flow).

The model was first used to investigate the limitations due to radiation losses alone in achieving high temperature solar sustained pure cesium plasmas. The energy balance calculations were carried out with a computer program. A flow chart of the complete program can be seen in Figure 2. The temperature was calculated by balancing absorbed energy from the dimer and photoionization transitions with the *spontaneous emission and recombination*. Blackbody radiation at a temperature of 5,800°K was used as the solar spectrum. The results from this analysis are shown in Figure 3. The maintenance flux and concentration ratio to sustain a plasma at a desired temperature is given.

The theoretical formulation of the model is based on the following argument. If the assumption is made that the system absorbs and emits radiation at one transition in steady state, then the energy balance can be written as:

$$P(\nu) \ \sigma \ (n_e - n_u) = n_u A \ (h\nu);$$

where:

n_u and n_e are the population densities at the upper and lower levels of the transition respectively;

h is Planck's constant;

σ is the absorption cross section;
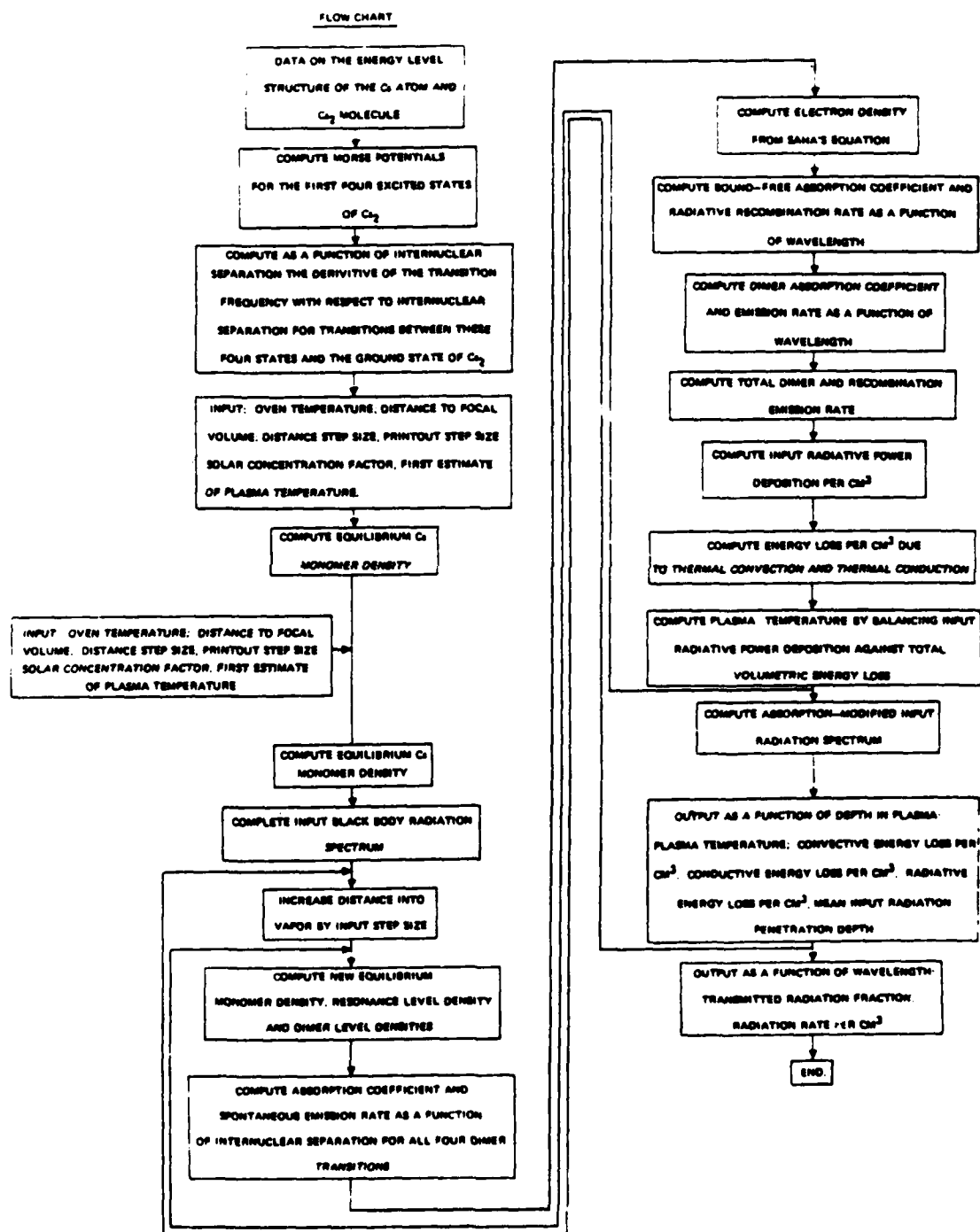
A is the spontaneous emission rate;

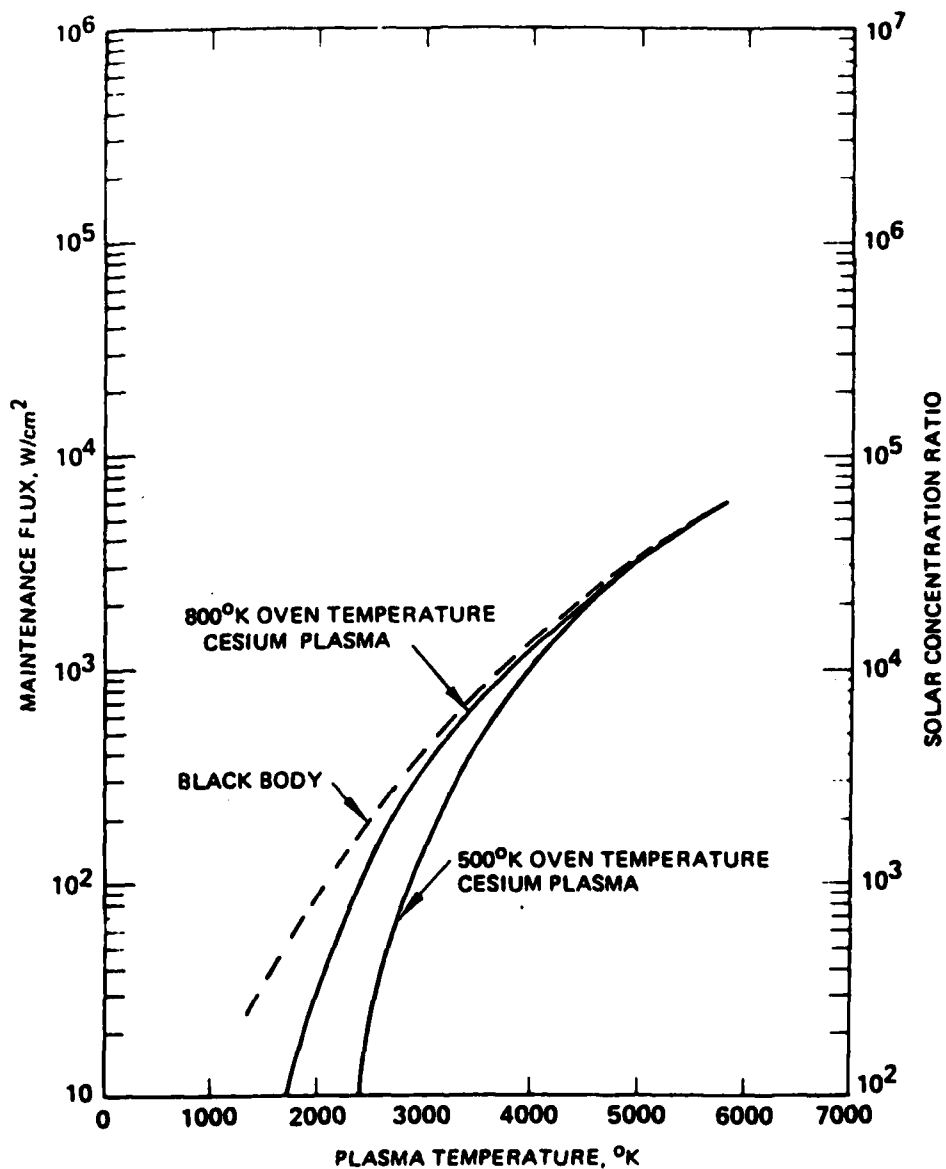Figure 2. HRL Theoretical Model (Computer Program Flowchart). (Ref. 24)

Figure 3. HRL Results from Radiation Loss Analysis. (Ref. 24)

$P(\nu)$ is the power flux at the transition wavelength;

and ν is the frequency.

Assuming transition level populations at a temperature T, are in thermal equilibrium, then the Planck's spectrum $P_T(\nu)$ is:

$$P_T(\nu) = \frac{2h\nu^3}{c^2}(e^{h\nu/kT} - 1)^{-1},$$

where k is the Boltzmann's constant.

If the radiation from a body at temperature T_R is to maintain the system at a temperature T, then the energy balance is:

$$C\, P_{TR}(\nu) = \frac{A}{\sigma}(\nu)\,\frac{nu}{ne}\bigg|\,T = P_T(\nu).$$

If $T_R \neq T$, then $C = P_T(\nu)/P_{TR}(\nu)$. To have blackbody radiation, C must be less than or equal to one where C greater than one is optically impossible. These statements hold for a system absorbing blackbody radiation from the continuous dimer and bound-free transitions. The necessary conditions for this analysis to be valid are that the system energy balance be dominated by radiation, that thermodynamic equilibrium exists, and the absorbed radiation is from a blackbody radiator. Because with lower temperatures radiation losses will become less dominant, Palmer and Dunning added conduction and convection to the model. The convergence of the beam has also been accounted for in the model. For consideration of using the plasma in a working cycle, one-dimensional flow was finally added.

According to Palmer and Dunning, the predictive power of this model is very good considering the difference between the assumed blackbody radiation and the solar spectrum. The model is a realistic description of the physics involved. This can be seen by comparing the Morse Potentials calculated by the model and the measurements made by Weschler[25]. Figure 4 Shows a comparison between the absorption cross sections calculated using Weschler's measurements and the Morse potential model. The two sets of values are in good agreement. With the material presented by Palmer & Dunning, the model does appear to be very accurate; however, futher investigation is needed to determine if all parts of the model are accurate.
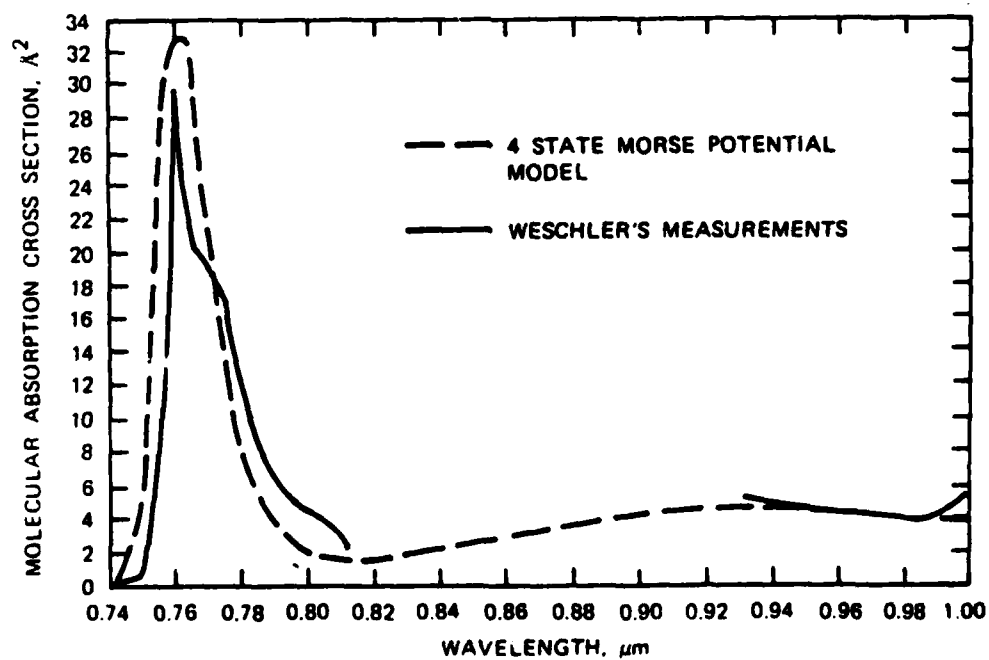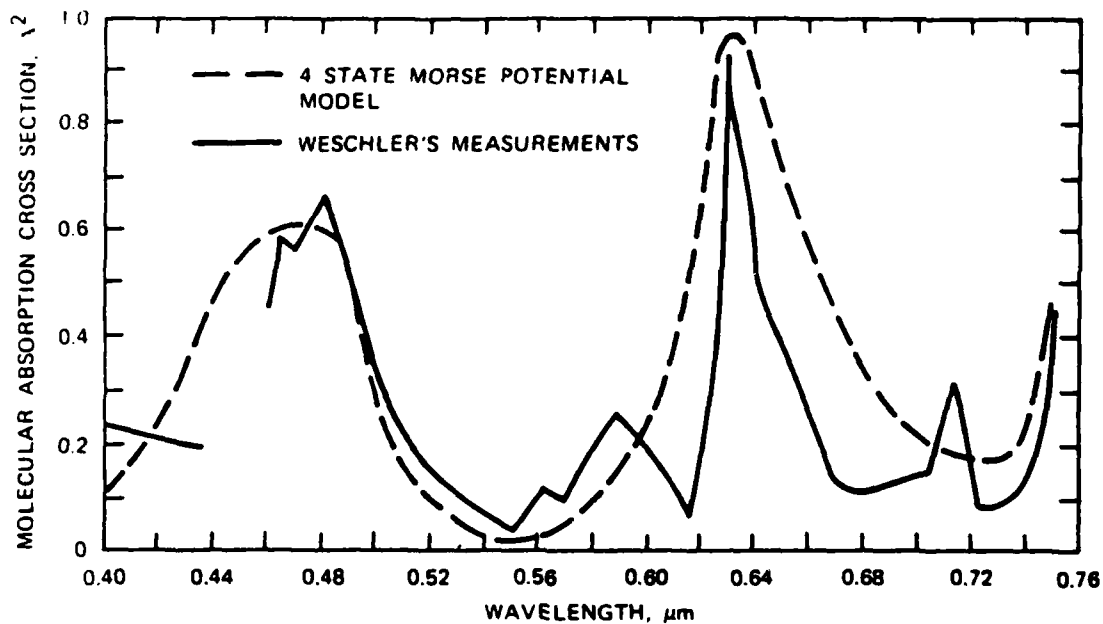
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Figure 4. HRL Comparison Between Absorption Cross Sections Obtained from Weschler's Measurements and the Morse Potential Model. (Ref. 24)

2.2.3 <u>Solar Experimental Research</u> - In recent years, there has been some attention focused on solar thermal propulsion. With this increased interest, experimental research has finally begun. Rocketdyne has recently designed and is presently fabricating a solar rocket under contract with AFRPL.[1] This thruster will be tested in-house using the existing RPL solar furnace. Testing is scheduled to begin within a year.

This thruster will use an indirect absorption process (heat exchanger type) to heat a propellant. A 10,000 : 1 area ratio concentrator will beam solar energy into the thruster which will be contained in a vacuum chamber. The chamber, thruster, and thrust stand are shown in Figure 5. The concentrated sunlight will be focused on a series of rhenium coils that are wound tightly into a cylinder. Hydrogen that flows through these coils will be heated, expanded, and ejected to create thrust. The design goals for this ground test thruster are 800 seconds Isp and 0.8 lb thrust.

The maximum temperature that can be reached in this thruster is approximately 2,700°K. Excessive creep and loss of structural strength will occur at higher temperatures. As mentioned, higher temperatures would yield better performance. Direct absorption concepts of solar thermal propulsion devices can withstand temperatures that are closer to the theoretical limit (5,600°K). To achieve higher performance goals, research must focus on direct absorption processes.

Hughes Research Labs (HRL) has recently completed research in the area of coupling solar radiation to fluid flow.[24] They were concerned with direct absorption processes with pure alkali vapor as the collector. The purpose was to characterize absorption so that a high temperature Rankine cycle energy converter could be designed for generating electric power in space.

Palmer and Dunning characterized the absorption of pure cesium vapor. Two radiation sources were chosen for experimentation. The first was an outdoor solar concentrator (fresnel lens) mounted on an equatorial tracking unit. This collector was capable of delivering 84 W/cm^2. The second source, chosen for indoor use, used a 1,600 W Xenon arc lamp with a 10-inch diameter elliptical reflector to simulate concentrated sunlight.
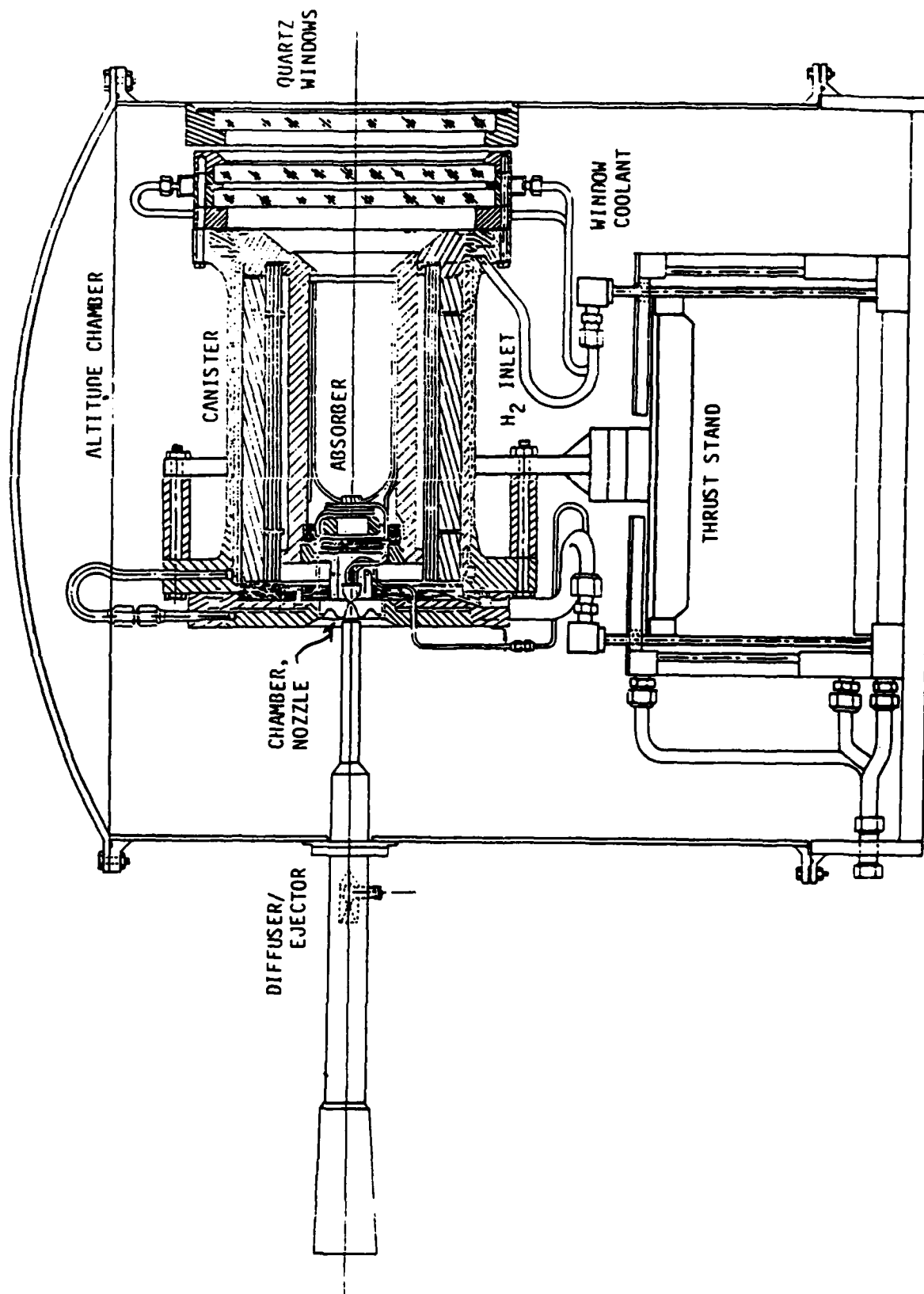
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Figure 5. AFRPL Solar Thruster, Chamber and Thrust Stand. (Ref. 1)

Labels in figure:
QUARTZ WINDOWS
WINDOW COOLANT
ALTITUDE CHAMBER
CANISTER
ABSORBER
H₂ INLET
THRUST STAND
CHAMBER, NOZZLE
DIFFUSER/EJECTOR

The original cesium vapor cell was designed by ILC Corporation. The design is shown in Figure 6. A 1-inch diameter sapphire window was used to admit the radiation. In the experiments, severe window fogging occurred and continued to occur even when high power window heaters were installed. Cesium vapor was depositing on cooler surfaces which included the windows. The ILC design was eventually abandoned after the window cracked twice. Absorption of far-IR radiation was believed to be the cause of window failure.

HRL decided to convert the absorption cell design to that of a heat pipe oven. A series of iterations in the design finally led to the one pictured in Figure 7c. The other designs are shown in Figures 7a and 7b. Conical baffles were installed in this oven to keep the cesium vapor from condensing on the window surface. The baffles were kept cool by a series of convection cells. The radiation was focused in the mid-region of the heat pipe with the lower end closed. When operated in the vertical mode, the cesium would drain back into the central region after condensing on the baffles. This kept the windows clean and cool. The focal region of the heat pipe was viewed through the entrance window using an optical multichannel analyzer on a shielded aligned optical train. The optics also consisted of a ¼ m Jarrel ash monochromator and vidicon tube assembly. These diagnostics allowed temperature measurements and heating signature traces (absorption profiles) to be made with ease.

The original cesium vapor cell could be maintained at temperatures between 500 and 600°C for indefinite periods. The window did not fog as long as illumination time by the solar simulator was kept between 1 and 2 seconds. Solar heating and plasma formation were first observed in this absorption cell. Window fogging, however, prevented interpretation of the data. When the HRL heat pipe was used, plasma formation occurred and three different signatures of plasma heating were observed.

Experimental measurements found the temperature of the gas to be 1,528°K for one estimate and 1,320°K for another. Theoretical calculation of temperature from the model described in Section 2.2.2 was made and predicted the temperature to be 1,800°K. Palmer accounts for this discrepancy as lack of blackbody radiation from the Xenon arc lamp which is assumed in the theoretical model.
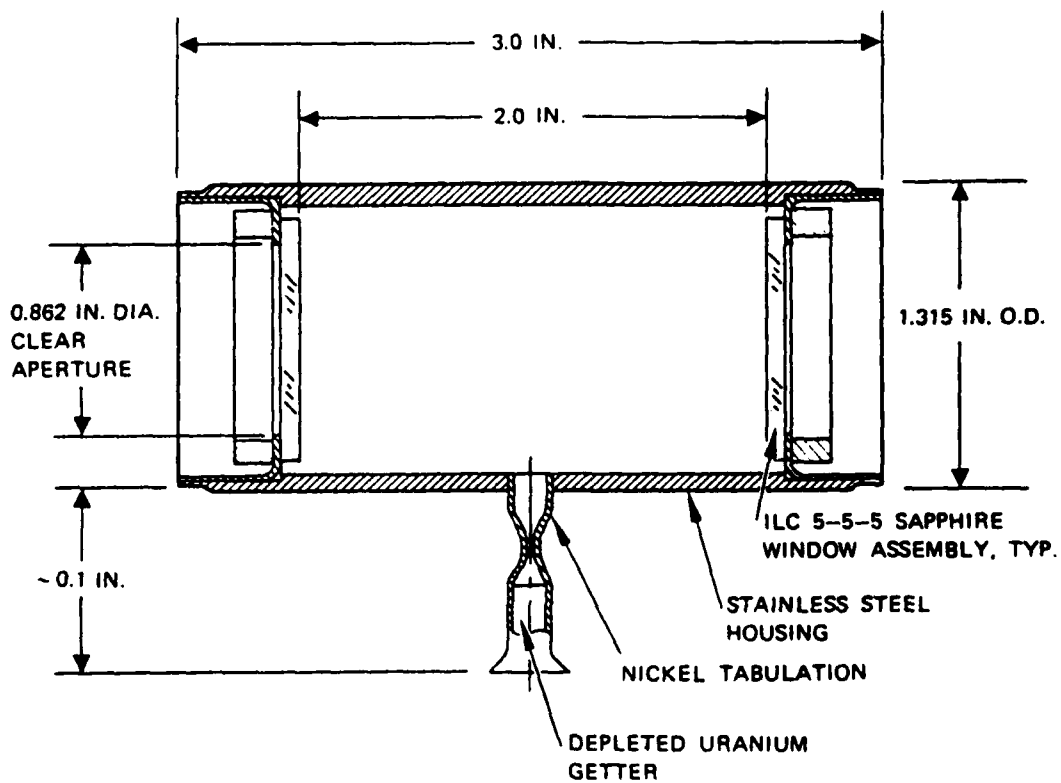
NOTES:

1. DEVICE VACUUM BAKED AT 600°C

2. FILLED WITH 10 ~ ¡ CESIUM

Figure 6. The ILC Corporation Absorption Cell for the HRL Research. (Ref. 24)

COOLING COILS   KOVAR   NO. 7052 GLASS

NO. 304 STAINLESS STEEL MESH

INCIDENT RADIATION FIELD

STAINLESS STEEL

(a)

Earliest

CONVECTION CELL

(b)

CONVECTION CELLS   CONICAL BAFFLES
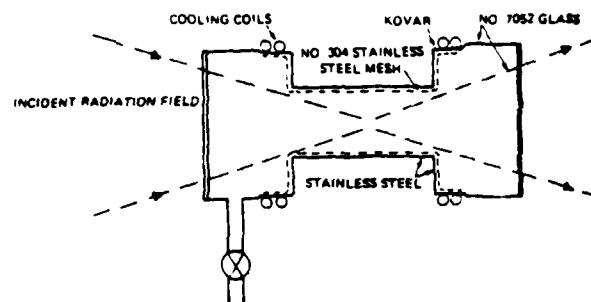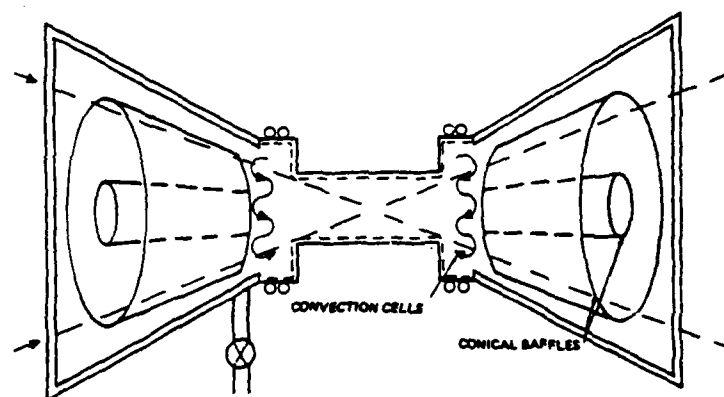
(c)

Latest

Figure 7. Design Iterations for the HRL Heat Pipe Oven. (Ref. 24)
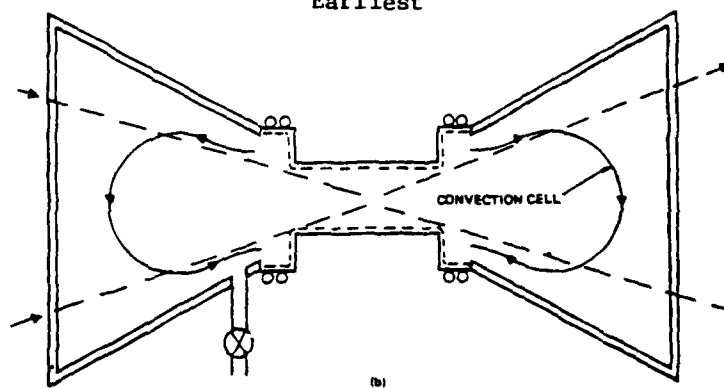
A second generation cesium cell was designed and manufactured after these experiments were completed. The new design contained precision baffles and transverse viewing ports. Funding limitations prevented further research from taking place. The HRL research is significant in that it is perhaps the first experimental program to sustain a plasma with a direct absorption process using solar or simulated solar energy.

Didier Rault, in thesis work performed at the University of Washington, also studied the concept of a solar radiation energy receiver.[26] Rault was interested in the application of the absorbers for use in energy conversion cycles. Potassium vapor was chosen as the collector and a potassium vapor 3-D radiatron receiver was designed. This receiver is shown in Figure 8.

Pure potassium vapor was obtained using a complicated boiler and feed system. This system was a closed-loop device and was constructed from materials compatible with the alkali metals. This design originated from a study by Rault[27] that examined methods of handling potassium metal safely. More discussion on handling and safety will be presented in Section 3.0.

The radiation was provided by a solar simulator. The simulated solar beam was obtained using a 6,000 W Xenon arc lamp. The light was concentrated using an electropolished stainless steel aspheric mirror. IR dichroic filters were used to reflect the broadened radiation. The illumination system simulated 6,000°K blackbody radiation which models the solar spectrum above the earth's atmosphere.

Sapphire windows were used in this experimental apparatus to transmit the simulated sunlight. Sapphire was chosen because of its wide spectral transmission, high temperature strength, and its chemical inertness. The inner window pictured in Figure 8 must sustain higher temperatures than the outer window. For this reason, a low thermal expansion window mount was designed for the inner window to ensure survivability. The assembly consisted of a sapphire disc (window) brazed to a Kovar metal sleeve with an inner sapphire ring. This allows thermal stresses in the sleeve to be balanced. This system survived a number of tests but was shut down when the inner sapphire ring failed.
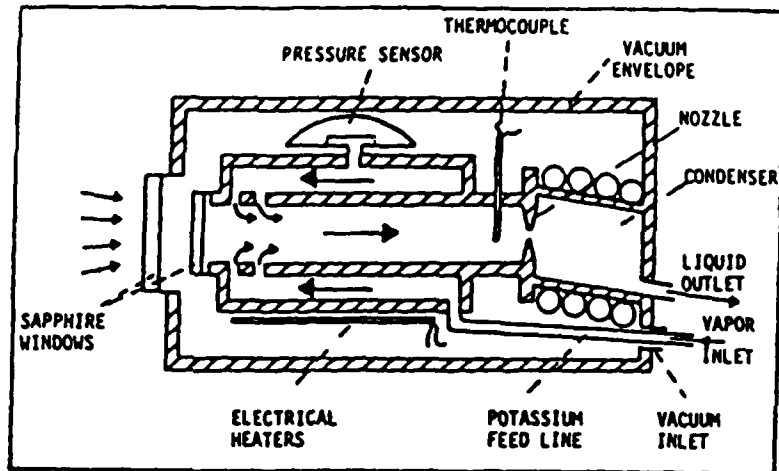
22

Figure 8. Rault's Radiation Receiver. (Ref. 26)

The objective of this research was to measure the efficiency of the receiver. This was to be accomplished by measuring the enthalpy increase in the fluid flow through the receiver. Due to the small dimensions of the absorber, temperature measurement of the flowing gas was very difficult. Thermocouple probes were chosen for this task. Pressure, mass flow, and light beam spectral distributions were the parameters varied in these experiments.

According to Rault, the experimental results are imprecise. The scope of the investigation was limited due to the engineering difficulties and operational safety requirements. The low sensitivity and poor accuracy of the thermocouples added to the overall inaccuracies (probes were characterized by low L/D ratio). Due to these limitations, evaluation of Rault's theoretical calculations was not possible.

It is obvious that research in the area of solar radiation absorption for propulsion has just begun and is very limited. An accurate theoretical model of the physics involved must be completed with good experimental verification. The HRL research is the work that most closely meets these requirements.

3.0 OTHER TECHNICAL ISSUES

In the previous sections, experimental and theoretical research that has been accomplished was presented and discussed. Facts about alkali absorption characteristics were also reviewed. This section presents technical issues or questions that are not extremely pertinent to a first stage experimental design, but are questions that must be answered or problems that must be solved before an actual thruster can be fabricated.

3.1 Window Design Considerations

Designing a window for a laser or solar absorption chamber (thruster) is a very difficult task. One must consider transmission and absorption characteristics of the window. Strength and thickness are also important factors. Compatability with the propellant is another important design configuration. The window must be able to support a pressure differential while allowing sufficient radiation to pass into the absorber. The window must remain cool to prevent excessive thermal loading. Throughout the research, there has been a variety of window designs. Diamond windows were used in the AERL thruster.[12] A zinc selenide window was used in the UTRC experiments.[9] These windows were relatively small in diameter and were designed for laser radiation.

Window designs for a solar radiation receiver are more difficult to achieve. The solar spectrum consists of a wide band of frequencies. An efficient window must allow all wavelengths to pass without absorbing strongly at frequencies where the flux is large. Windows for solar absorption chambers are typically larger than laser windows and therefore must be stronger or thicker. Some solar window design concepts are shown in Figure 9.

One concept of a window design suggests the use of propellant flow across the window.[28] This would maintain the window clean and cool. The AFRPL solar thruster uses a double pane system with FC77 (a commerical mixture of perfluoroethers) coolant flow between the panes. This cooling is necessary because the window is made of Corning fused silica which absorbs at wavelengths in the UV and in certain IR regions. Because this is a heat
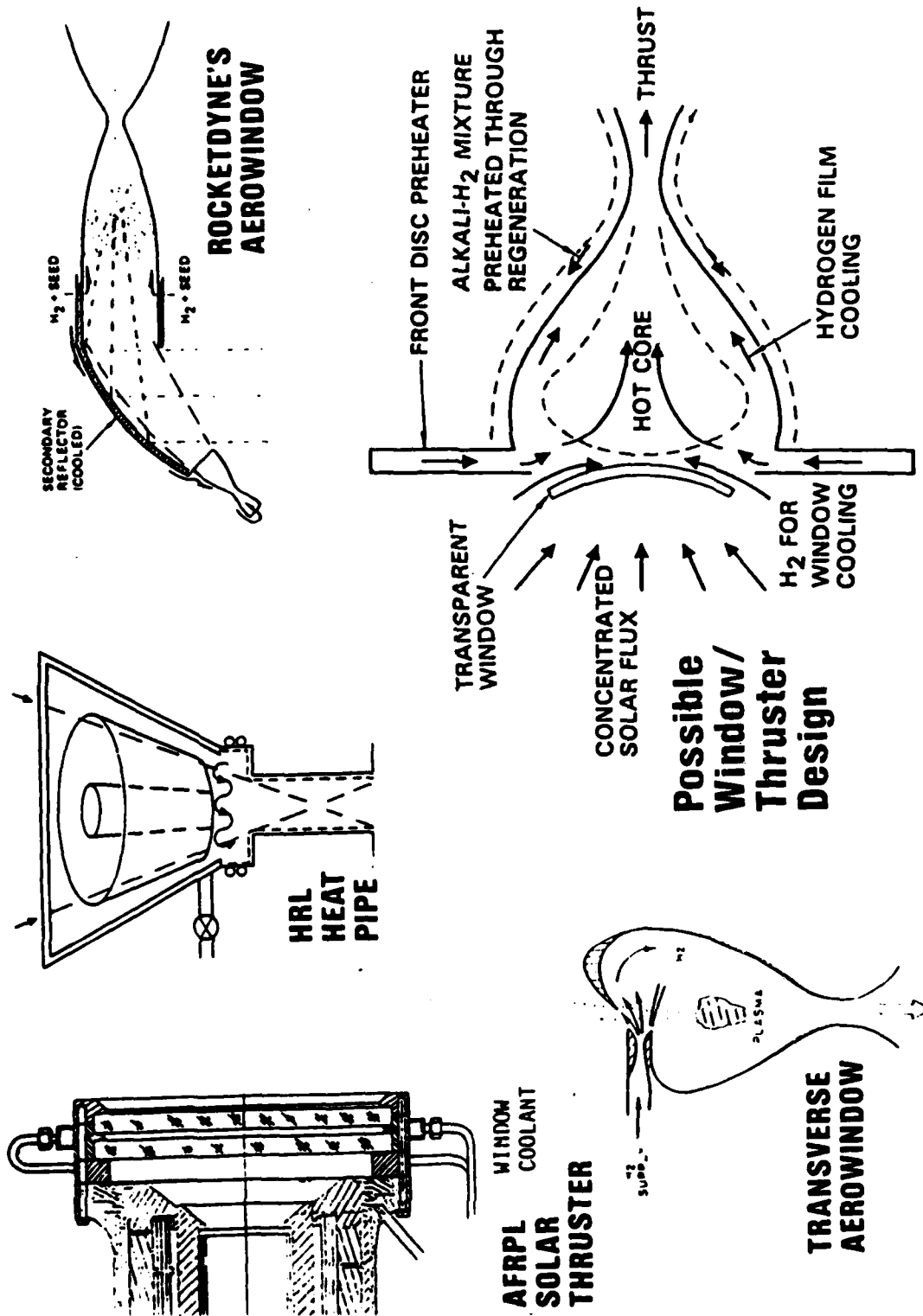
Figure 9. Some Existing Solar and Aerowindow Designs.

exchanger type thruster, the windows will only be needed for ground tests and may be removed for space applications. The HRL heat pipe windows were located far from the absorption zone to prevent excessive thermal loading. Conical baffles protected the windows from condensation. This was a second generation design due to the failure of the sapphire windows in the original heat cell design.

A possible solution to these design difficulties is to use a non-solid material window or "aerowindow." Aerowindows have conceptually been considered but research is insufficient to prove or disprove the idea. There has been a large amount of work done on aerowindows for gas dynamic lasers.[29-31] These aerowindows operate with the reverse pressure ratio needed for an absorption chamber window. Atmospheric pressure is greater than the pressure in the laser cavity. An aerowindow for an absorption chamber must be able to withstand a pressure differential where the pressure is greater in the chamber than the surrounding environment.

The confining feature of an aerodynamic window comes from the supersonic flow that exits a nozzle. The gas, which would be a propellant for absorption chambers, flows across the orifice where a conventional window would normally be placed. A series of shock or expansion waves will occur which helps prevent leakage. Hydrogen gas is of primary interest for aerowindows since it is a propellant and is transparent to radiation at low temperatures.

The main concern with an aerowindow is the leakage. As the chamber pressure rises the leak rate can also be expected to rise. This concern was not as large with aerowindows for lasers because the pressure difference was small. Free vortex aerodynamic windows were developed to expel any leakage that occurred. It should be noted that larger diameter windows will have larger leak rates.

At present, a fully successful aerodynamic window for an absorption chamber has not been designed. There are, however, many conceptualizations.[32] Some are shown in Figure 9. The only experimental research with aerodynamic windows for absorbers was presented by AERL.[33] A schematic of the laser thruster containing the aerowindow is shown in Figure 10. The window diameter

0 WINDOW CHAMBER   5 ABSORPTION CHAMBER
1 WINDOW THROAT   6 NOZZLE
2 SUPERSONIC WINDOW FLOW 7 NOZZLE EXIT
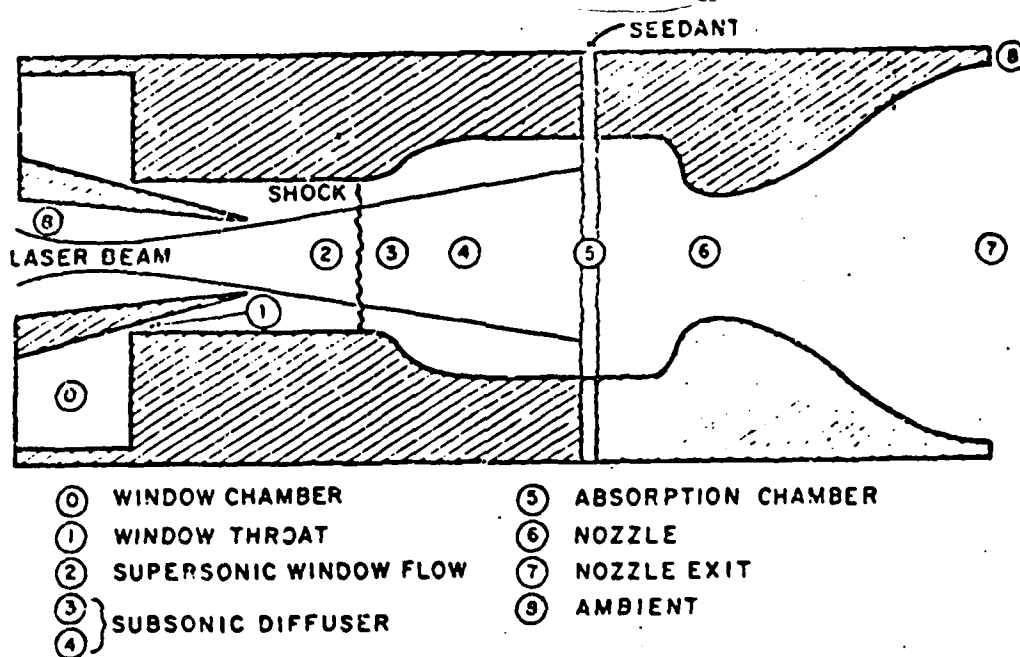3 } SUBSONIC DIFFUSER   8 AMBIENT
4 }

Figure 10. **AERL's Aerodynamic Window for a Laser Thruster.** (Ref. 33)

was one centimeter and the plenum for the window was filled with nitrogen. The throat spacing was 0.5 millimeters yielding a diffuser velocity of Mach 3.5 and a pressure of 0.33 atmospheres. The plenum pressure was varied from 50 to 600 psia. At plenum pressures under 120 psia, the leak rate varied from 2 to 8 percent. Once the plenum pressure was brought above 120 psia, the leak rate remained below 2 percent of the total mass flow. According to AERL, the aerowindow in a realistic possibility for laser propulsion systems.

The success of this design may not be as promising as suggested. The chamber pressure was never mentioned. This is an important parameter that should have been varied. The window diameter was set to 1 centimeter. Windows for solar absorbers would be much larger. The diameter of the window should also have been a variable. The feasibility of aerowindows is still questionable and more research is needed.

3.2 Hydrogen Alkali Mixing and Safety

Introducing an alkali seed into a hydrogen flow is not an easy task. Mixing facilities must be designed that can properly seed the hydrogen while keeping the immediate environment safe from alkali contamination. A few techniques were developed in the research with alkali metal absorption.

In the AERL laser absorption thruster, hydrogen gas was seeded with cesium.[12] An injector was developed for this purpose. The seeding was accomplished by flowing cold hydrogen gas over a molten bath of cesium. This produced an aerosol of fine cesium particles (solid) that could be transported with the flow. To avoid contamination, a glass ampoule was filled with cesium and placed in a chamber. The ampoule was broken with a blast of compressed nitrogen. The cesium was released and entered a heating pipe which controlled the bath temperature. The hydrogen gas was cooled by circulation through a copper pipe that was immersed in liquid nitrogen.

The concentrations of cesium could be controlled by changing the bath temperature but quantitative control of the concentration was difficult. It was possible for the cesium particles to collect in the kinks and crevices of the plumbing from the bath to the thruster. It is also possible that the cesium melted and adhered to the walls of the piping. For actual calibration, it would proabably be necessary to measure the seedant concentration in the exhaust.

In optical pumping experiments with dense alkali vapors,[34] Happer and associates noticed small particle formation when the system was illuminated with resonant laser beam radiation. With further experimental investigation, it was found that these particles were formed by an alkali reaction with hydrogen that contaminated the system. To examine this phenomenon further, a hydrogen alkali mixing facility similar to the AERL system was designed and fabricated. Dr Happer[35] cautions that hydrogen alkali mixing can be dangerous. He states that the danger arises from the hydrogen. If large amounts of hydrogen are exposed to air or oxygen, an explosion can occur. When pure alkali is exposed, only a fire can occur. The burn rate of the alkali is slower than hydrogen because oxidation can only occur at the surface of the alkali.

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The exhaust from a thruster or experimental chamber is also hazardous. It will contain alkali in some form. If the liquid state is present, the alkali can adhere to the nozzle walls and spatter out the exit plane. Research to examine exhaust and mixing hazards is necessary before experimentation can take place.

There are a variety of other issues or questions that deserve mention to make the reader aware of future complications. These questions can only be answered with additional theoretical or experimental research. The items of concern are:

o   Kinetic losses in the nozzle increase with a nozzle area ratio increase. Can these losses be controlled for a set of design parameters?[36]

o   Reradiation has not been accounted for in theoretical models. What effect will this have on performance?

o   Diatomic alkali hydrides will form in the presence of solar or laser radiation. This will increase the spectral absorption range of the propellant due to absorption in near UV. How much will this raise the bulk temperature of the gas?[28]

o   Recombination of hydrogen or alkali in the nozzle can increase performance but recombination near the chamber walls can cause excessive wall heating.

o   Alkali deposition or condensation on cooler surfaces can cause corrosion and loss of performance.

o   Instabilities may arise from poor propellant injection techniques. How can we ensure stable ignition?

o   Dynamic instabilities may occur. Cooling of the gas near the plasma throat may take place. This will cause the local absorption coefficient to decrease and the mass flow to increase. This could have an overall cooling effect which could cause the plasma to self-extinguish.[36]

o   Bouyancy induced instabilities may arise due to density variations in the gas.[36]

o   Radiation absorption can cause acoustic instabilities.[37]

4.0 RECOMMENDATIONS AND CONCLUSIONS

With the theoretical and experimental research that has been done in the laser and solar thermal propulsion area presented, it is now possible to develop a new research program. This plan will focus on using alkali seeded hydrogen as the working fluid for a direct absorption solar thermal propulsion device. The program will be divided into theoretical and experimental research. The recommendations will be based on the information presented. The work plan will be designed to avoid the failures encountered in the past, to correct errors that have been made, and to advance the science to a degree where solar thermal propulsion becomes a reality.

4.1 Theoretical Research

With a model that can predict absorption length, power input, and radiation losses, a good predictive theoretical model can be developed as shown in Figure 3. This model accounts for the three forms of heat transfer, convection, absorption, and 1-D gas flow. The model can calculate the temperature as a function of axial distance through the absorber, the properties such as convective energy loss, conductive energy loss, radiation losses, and optical depth. As a function of wavelength, the radiation losses and radiation transport rate are also available. These results are provided on a theoretical basis.

It is mentioned in the report that the predictive power of the model is good. The calculated cross sections for cesium agreed with Weschler's measurements. To determine the validity of the model, it is necessary to input the atomic structure of other alkali metals. The calculated cross sections can then be compared to the other existing theoretical data to determine the validity of the model. Theoretical, continuous absorption profiles for other alkali metals should be obtained from the available literature by the method described in Section 2.2.1. to be used for comparison.

The Hughes method assumes that there is no reabsorption of radiation (optically thin). Theoretical research is needed to determine the validity of

this assumption. Reabsorption may play an important role in the overall absorption process. It may be necessary to include this in the model. Also, the theoretical model is one-dimensional because it was developed for energy conversion cycles. For the application being considered in this document, using the working fluid for propulsion, it is desirable to expand the 1-D flow model to two-dimensions. This is important to better understand the physical processes and determine performance.

Because this model was developed for the interaction of sunlight with a pure alkali, it is necessary to determine how the addition of hydrogen into the working fluid affects absorption. It is important to theoretcally determine the species concentration of the alkali metals (negative ions, positive ions, dimers, etc), the reaction rates, and the collisional transfer rates from the excited alkali atoms and dimers to the hydrogen. This will enable better prediction of absorption coefficients for the hydrogen-alkali mixture and a better understanding of the physics of the processes (or mechanisms) involved.

Because laser radiation consists of only one wavelength of light, it is only necessary to have one dominant absorption process. A wide band of frequencies of light are present in solar radiation, therefore it is necessary to have absorption processes occurring across the spectrum. It is much more difficult to find a working fluid that can efficiently absorb, at least to some degree, over this broad range. The most likely seedants for the hydrogen will be a combination of sodium and potassium. Potassium has a "window" in the green band. Sodium absorbs in the green and the overall absorption of the combination would resemble that of blackbody. Lithium is another seedant possibility. Little is known about lithium absorption but it is known that it reacts strongly with hydrogen. Although this reaction is not favorable, the possibility of using lithium as a seedant should be examined closely because of its low molecular weight.

Material windows (quartz or sapphire) will most likely be used in the experimental absorption chamber. It is not possible to use aerodynamic windows now because there is insufficient research available to prompt a design. Theoretical research is needed in this area. Aerowindows may indeed by feasible and may simplify thruster designs.

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A theoretical investigation into the effects of recombination of propellants near chamber walls and in the nozzle must be made. Recombination is an exothermic process. Large heat loads at the walls may occur if recombination takes place. This would be detrimental to the thruster or experimental device. Recombination in the nozzle, because of the heat release, may prove to be advantageous; however, condensation of alkali in the nozzle may result in a performance loss. The alkali may adhere to the nozzle walls and spatter out the exit plane. This would also be very hazardous. It is proposed that clean gas boundary layer injection be used to alleviate this problem. Analytical investigation is needed.

4.2 Experimental Research Plan

If the theoretical results are promising, experimental research should be made in the area of aerodynamic windows. Leak rates of window designs should be characterized for a variety of chamber and plenum pressures, window diameters, and flow rates. This variation in parameters is essential to determine the actual feasibility of aerodynamic windows.

It is imperative to experimentally study the absorption process of the hydrogen-alkali mixture. Reaction rates, species concentration, optical depth, and temperature are important parameters to be measured. The effect of alkali concentration on absorption and performance is also important. At this time it is not known whether "solar supported combustion waves" will result from absorption. It is crucial that the gas dynamics and heat transfer properties of the working fluid be characterized so than an understanding of the phenomena and evaluation of the theoretical formulations can be made. Refining of the theoretical model may then be appropriate after consideration of experimental results.

Probe lasers, detectors, and spectrometers may be used to determine some of the properties of the working fluid. The concentration of hydrogen ions can be determined from the Raman scattering laser diagnostic technique.

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Thomson scattering or Langmuir probes can be used to obtain electron densities. Alkali metal ion concentrations can be determined using fluorescence. These parameters are important in determining the transitions or absorption processes occurring.

Efficiency of the absorption cell is determined by measuring the enthalpy increase of the working fluid. Temperature measurements can be made with the spectroscopic equipment recommended by Hughes. The photomultichannel analyzer and vidicon tube assembly with monochromator are commercially available. Plasma heating signatures may also be obtained by using this same diagnostic equipment.

It was mentioned in Section 3.0 that diatomic alkali hydrides may form in the presence of light. If these hydrides form, the spectral range of the propellant will increase due to IR absorption. Investigation of this phenomenon should be made during experimental research. Also, the degree of condensation and deposition of the alkali metal on cooler surfaces should be determined. Corrosion and loss of performance may become too large as a result of the condensation.

Stability of the solar supported plasma may depend upon the propellant injection technique employed. Poor injection may cause the plasma to extinguish due to dynamic instabilities or breakdown may never occur. Mixing of the alkali and hydrogen gas must also occur safely. Research in mixing techniques should be a part of the experimental program.

It is important to suggest an experimental absorption chamber design. The absorption cell that may be most useful is pictured in Figure 11. It resembles the NASA Marshall-AFRPL diagnostic chamber designed to study absorption of hydrogen-water mixtures. Recall that the temperatures necessary for absorption measurements are obtained using the thermal absorption wave. The suggested experimental apparatus will not utilize the thermal absorption wave.

Solar radiation enters a windowed port. The frustrum of the conical entrance converges with the solar beam (approximately 45°). This allows the

SOLAR PUMPED PLASMA DIAGNOSTICS
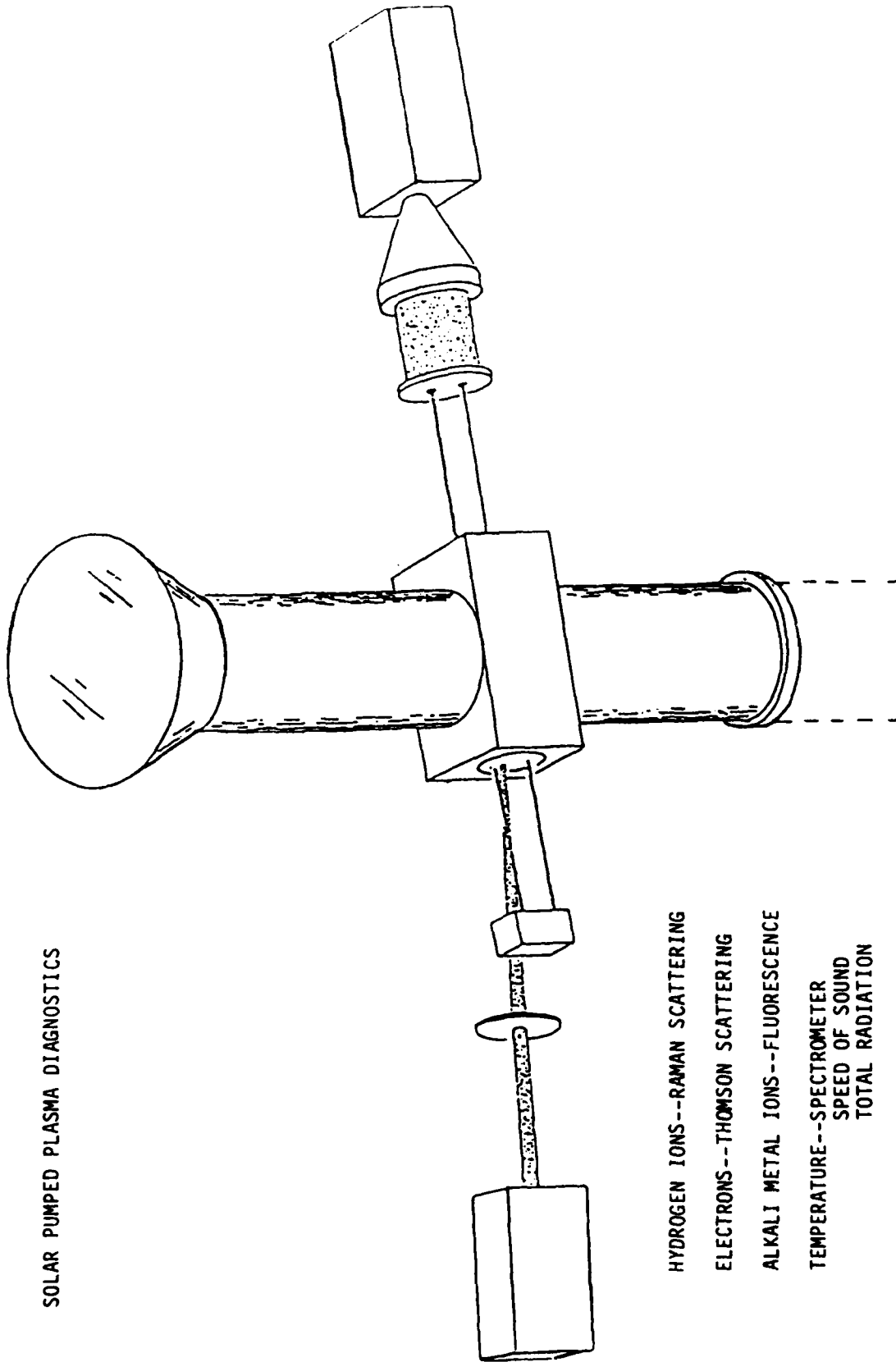
HYDROGEN IONS--RAMAN SCATTERING

ELECTRONS--THOMSON SCATTERING

ALKALI METAL IONS--FLUORESCENCE

TEMPERATURE--SPECTROMETER
          SPEED OF SOUND
          TOTAL RADIATION

Figure 11. Possible Research Apparatus for Solar Plasma Physics Studies.

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entire beam to enter while keeping the window away from the high temperature zone. The window will be made of a highly transparent, strong, inert material. Sapphire or fused silica (quartz) will most likely be the choice.

The diagnostic region will be located at the high temperature or plasma zone. The chamber will be designed for both static and dynamic research. A nozzle extension capable of producing choked flow will be included in the dynamic research for performance measurements. The diagnostic region will contain windows for the laser experimental measurements. Large heat loads may cause the windows to fail. For this reason, extensions from the central region may be required. This will not affect the measurements but may perturb the flowfield. At least two diagnostic windows will be needed: one for admisssion of the probe laser beam and the other for detection.

Whether the design and fabrication of the experimental apparatus is done in-house or under contract, the actual research should take place at the AFRPL 1-14 Solar Facility. A three year research program is envisioned. Design, fabrication, and build-up will occur during the first year. The remaining two years will focus on experimentation, measurement, and analysis of data. This research must be accomplished as soon as possible in that it is the necessary first step toward flight of a solar thermal propulsion unit.

5.0 SUMMARY

The concept of a solar thermal propulsion device is defined. The advantages and disadvantages over laser and conventional propulsion are stated. The theoretical and experimental research that has been done on laser thermal and solar thermal propulsion is presented with the emphasis on experimentation and diagnostics. A brief description of other technical issues that are secondary to a first stage design is also given.

With this background information, a future research plan was formulated that will answer some of the questions and fill in the gaps that are present in the current results. The program contains both theoretical and experimental research with an experimental apparatus and diagnostic technique suggested. This research is necessary to complete the first step in the evolution of solar thermal propulsion.

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APPENDIX

LASER RESEARCH REVIEW

List of Illustrations

PREDICTION MODELS FOR LASER ABSORPTION COUPLED FLOW

Prediction and experimental verification of the flowfield through a solar supported combustion wave or plasma is an important element of this research. Reported efforts of modelling such a phenomenon are rare but there are numerous works that approximate the flow through a laser supported combustion wave (LSCW). LSCW equations of motion may be used as the basis to begin an analysis of the solar sustained plasma flow.

The first analysis of coupling beamed energy to a flowing gas was accomplished by Raizer.[1] By using the approximation to the momentum equation that the pressure throughout is constant, the equations of motion were reduced to a single ordinary differential equation. The equation is basically an energy balance with the mass flux as an eigensolution. The solution shows that the intensity of the incoming beam specifies a unique propagation velocity. In an actual propulsion system where the flow accelerates through a converging-diverging nozzle, there are matching conditions that must be maintained. The mass flux specified by the beam intensity must match the mass flux specified by a choked flow given a set of upstream stagnation conditions. A converging beam alleviates this condition by allowing the wave to move to the proper intensity, thus broadening the solution.

Kemp and Root[2] expanded Raizer's work to include realistic property variations. Their analysis was basically represented by an energy conservation equation which included convection, laser absorption, radiation loss to the environment, radiation transport, and thermal conduction.

$$\frac{d}{dx} (\rho u H) + \frac{dI}{dx} + \frac{DS_A}{dx} + P_T = \frac{d}{dx} (\lambda_c \frac{DT}{dx})$$

$\frac{d}{dx}(\rho u H)$ = Convection term

$\frac{dI}{dx}$ = Absorption term

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$\dfrac{DS_A}{dx}$= Radiation Energy Transport Term

P_T = Radiation Loss Term

$\dfrac{d}{dx} (\lambda_c \dfrac{DT}{dx})$= Thermal conduction

Where

T   = Temperature;

ρ = Gas Density;

u   = Gas Velocity;

H   = Total Gas Enthalpy = $h + \dfrac{u^2}{2}$;

I   = Laser Intensity;

S_A = Radiation Energy Flux;

P_F = Radiation Loss Term; and

λ_c = Equilibrium Thermal Condition.

Kemp and Root also hold that the pressure throughout the wave is constant thus reducing the momentum equation to:

$$P = P_o$$

This is reasonable because velocity changes in the wave will be small making pressure changes generated by momentum changes negligible.

Using conservation of mass,

$$pu = \dot{m}_A = \text{constant},$$

and the equation of state,

$$P^{-1} = R_m Z T / P_o,$$

where R_m is the molecular gas constant and Z is the compressibility factor, the convection term of the energy equation can be written

$$\frac{d}{dx} (puH) = \dot{m}_A \left[Cp + (\frac{\dot{m}_A R_m}{P_o})^2 z^2 T (1 + \frac{d\ln z}{d\ln t}) \right] \frac{dT}{dx};$$

C_p = specific heat at constant pressure.

The laser absorption term can be derived from the laser energy transport equation

$$dI/dx = - K_L I,$$

where K_L = laser absorption coefficient.

Solving the equation gives

$$I = I_o e^{-\tau}, \quad \tau = \int_0^x K_L \, dx$$

where: τ = optical depth, and

I_o = incoming intensity.

Thus, Kemp and Root find

$$\frac{dI}{dx} = -K_L I_o e^{-\tau}.$$

A radiation conduction approximation method is used for the radiation transport term where the gas is considered optically thin;

$$\frac{dS_\Delta}{dx} = \frac{-d}{dx} (\lambda_R \frac{dT}{dx}),$$

where λ_R = radiation conduction.

Combining the above terms, Kemp and Root arrived at the complete energy equation

$$m_A \left[C_p + (\frac{m_A R}{P_o})^2 Z^2 T (\frac{d\ln z}{d\ln T}) \frac{dT}{dx} - K_L I_o e^{-\tau} + P_T \right] = \frac{d}{dx} (\lambda_c + \lambda_R) \frac{dT}{dx}.$$

The above equation is a second order differential equation for $T(x)$, the temperature distribution is an LSC wave. It is a general equation where the terms C_p, z, K_L, P_T, λ_c, and λ_R are dependent upon the gas used. Seedants will also affect these values. C_p, K_L, P_T, λ_c, and λ_R are defined in the appendices of Ref. 2.

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As mentioned before, the solution to the energy equation is an eigenvalue problem. For a laser intensity there is a unique mass flux ($\dot{m}_A$) that will allow a realistic solution. Kemp and Root found that if $\dot{m}_A$ is too high, the temperature profile will peak, fall, and then rise again; if $\dot{m}_A$ is too low, the temperature profile will peak and fall sharply. This can be seen in Fig. A-1. For $\dot{m}_A$ too high, the second rise is due to a energy source downstream; for $\dot{m}_A$ too low, the fall represents an energy sink downstream. These are physically unrealistic. Kemp and Root chose two values of mass flow for a laser intensity and iterated between them until they arrived at a partial solution as shown in Fig. A-2. Notice that the solution diverges after a certain point downstream. A realistic solution (temperature profile) should approach a finite value, T_ϕ, far downstream where the temperature would remain constant (no absorption and no radiation).

Keefer and coworkers[3] re-examined the Kemp and Root 1-D model in hopes of arriving at a full solution. Keefer agreed with Kemp's model but used a different solution method for solving the energy equation. Keefer divided the solution domain into two regions: $x = -\infty$ to $x = 0$ and $x = 0$ to $x = \infty$. The point $x = 0$ was taken where $T(x) = T_K$, the threshold temperature of absorption. Ordinary solution methods were used in the two regions with the following boundary conditions:

$$T(-\infty) = T_0 \text{ (injection temperature).}$$
$$T(\infty) = T_\phi ,$$
$$I(-\infty) = I_0 \text{ (initial intensity).}$$

Using this method, Keefer arrived at a full solution. The temperature profile matched that of Kemp and Root before the point of divergence and then asymptotically approached a finite value far downstream as shown in Fig. A-3.

For a one-dimensional analysis, the Kemp and Root model can be considered useful, however, the eigenvalue solution to the energy equation is only an approximation to a complete solution. The more accurate solution is given by the full Navier-Stokes flow equations. The Navier-Stokes equations are defined by Merkle[4] and will be discussed later. Kemp and Root have even further expanded on the eigenvalue model to couple LSC wave and stream tube
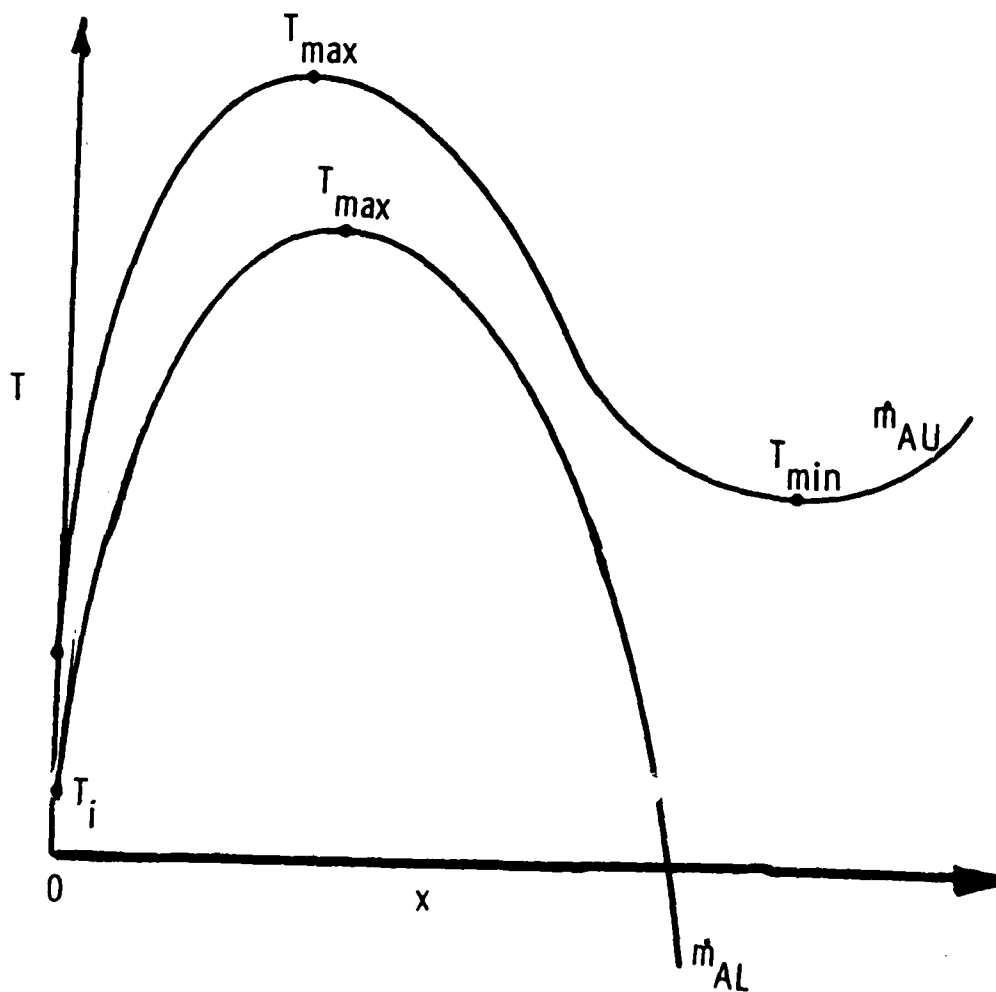
Figure A-1. Temperature Profiles Corresponding to Upper and Lower Values
of Mass fwx, m_a, for a Given Intensity.
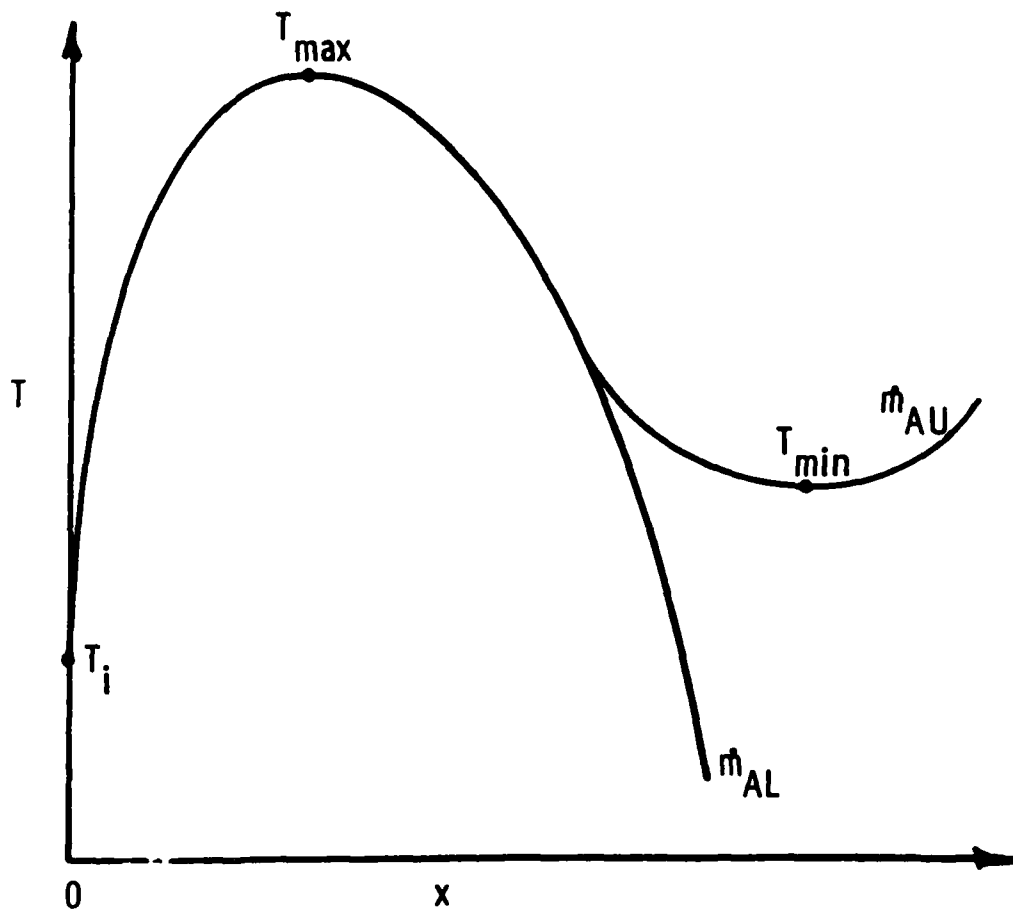
(From the Kemp and Root Model).

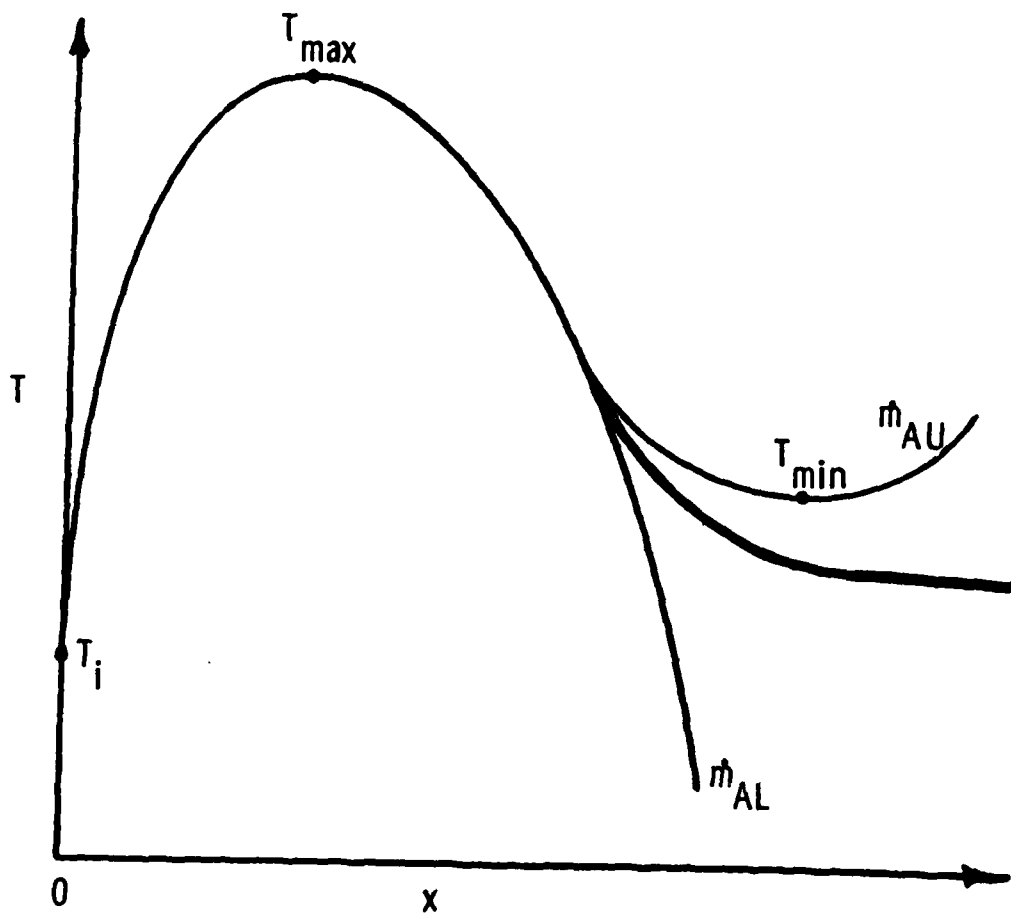Figure A-2. <u>Divergent Temperature Profile of the Kemp and Root Model.</u>

Figure A-3. **Keefer's Full Solution to the Energy Equation**
With Downstream Boundary Conditions Applied.

flow. They have also accounted for some two-dimensional effects. Kemp and Root simulated nozzle flow by adding pressure and area changes to the existing energy equation.

The analysis was used to obtain temperature and velocity profiles for a hydrogen plasma. The temperature rises and reaches a maximum quickly at the hot core and then falls off continuously through the throat and nozzle. The velocity profile shows a rapid but small rise to the maximum temperature location. The velocity then remains fairly constant, decreasing slightly in the LSC wave. During streamtube (nozzle) flow the velocity increases rapidly.

The one-dimensional model accounts mostly for heat losses occurring in the axial direction. The only transverse loss modeled is the radiation from small cylinders. Kemp and Root broadened the 1-D model to include radial convective losses and black radiation from the edges of larger plasma cylinders due to the radial temperature gradient. The radial conductive losses were estimated as

$$q_{rc} = \frac{1}{r} \frac{d}{dr} \left(r \lambda_c \frac{dT}{dr} \right)$$

where r = radial coordinate.

The assumption that q_{rc} depends on X only is made to preserve one-dimensionality which leads to

$$q_{rc} = \frac{-4}{R_i^2} \int_{T_e}^{T} \lambda_c \, dt$$

where T_e = edge temperature of cylinder and R_i = distance to edge. The edge temperature, T_e, is not known since the radial temperature profile is not known. Kemp and Root chose T_e to be the injection temperature which will give the integral its largest value. To compensate for this, the factor of 4 is reduced as suggested by Raizer. The factor is input as a "guessed" coefficient depending on laser intensity and the specific chosen parameters. A similar approximation is made for the radial radiation losses; thus, the complete term to be added to the equation is

$$\frac{C_{LC}}{R_1^2} \int_{T_e}^{T} \lambda_c \, dT + \frac{C_{LR}}{R_1^2} \int_{T_e}^{T} \lambda_R \, dT$$

where C_{LR} and C_{LC} are "guessed" coefficients.

Beam convergence also has a two-dimensional effect on absorption. The intensity will change axially with convergence. This affects mass flux and propagation velocity. In unconfined flow, the 1-D predictions of wave speed may be too low due to the neglect of transverse flow. Experimental wave speeds in air have indeed been higher than 1-D predictions. The phenomenon causing higher wave speeds is depicted by Kemp and Root in Fig. A-4. As the flow turns around the wave, the flow area increases causing velocity to decrease. Thus, the axial velocity near the wave is slower than that measured upstream. The measured wave speed will therefore be higher than predicted. In application, the flow will be confined in a channel so the expected effects of transverse flow are minimal. There are no theoretical models that account for transverse flow effects because of the difficulty in solving the 2-D equations. Likewise, no experimental characterization of confined transverse flow has been done.

This analysis of an LSC wave by Kemp and Root is the most extensive research reported. They have tabulated results for pure Hydrogen and Hydrogen-water-cesium mixtures for a variety of chamber and beam conditions. A computer program was written to aid in these calculations. The program is currently being used by NASA-Marshall for theoretical prediction of laser absorption in Hydrogen-seedant mixtures.

Keefer has also modeled the hydrogen laser supported plasma.[5] His analysis was an extension of the Batteh-Keefer model presented in 1974. Basically, Keefer's model was almost identical to the Kemp and Root model only written in cylindrical coordinates to obtain a 2-D solution.

Channel walls will restrict the radial component of flow. Assuming that the radial flow becomes negligible, the energy equation can be reduced to

$$\alpha \frac{d\theta}{dx} = \frac{d^2\theta}{dx^2} + \frac{1}{r} \frac{d}{dr} \left(r \frac{d\theta}{dr} \right) + SKv - \phi$$
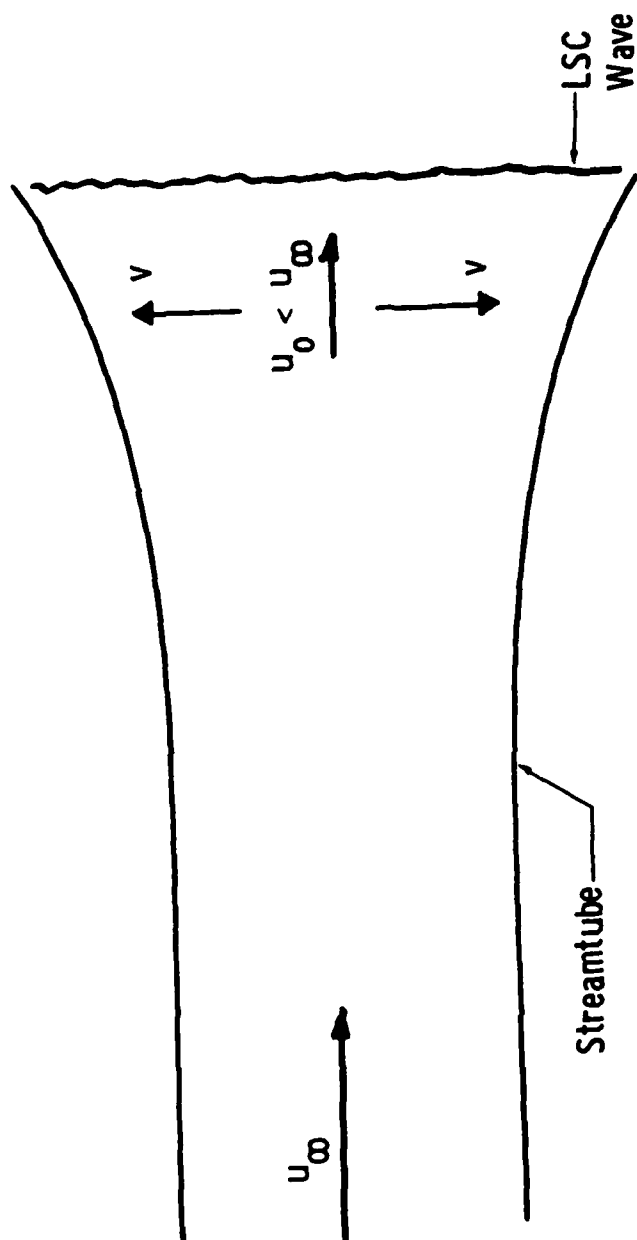
Figure A-4. Schematic of the Transverse Flow Effect.

where
$$\alpha = \rho_o\, C_p\, U\, /\lambda$$

and
$$\theta = \int_{T_o}^{T} \lambda\, T'\, dT'.$$

Approximations of the energy absorbed and the radiation loss were made in addition to assuming that C_p/λ_c is a constant. This linearized the energy equation so that a solution could be obtained. Basically, the equations were reduced to one dimension with temperature as the only two-dimensional variable. Keefer obtained results for a hydrogen plasma including the only two-dimensional temperature profile reported. This can be seen in Fig. A-5. Again, this 2-D analysis contains simplifying assumptions and does not represent a complete solution.

Merkle, recently, has formulated the radiation-gas dynamic interaction using complete Navier-Stokes equations.[4] This represents a more accurate solution in that no approximations are made such as incompressible or inviscid flow. Although the formulation is one-dimensional, it can easily be extended to two dimensions.

The solution to the Navier-Stokes equation is obtained using a time-marching procedure. Because of the nonlinearities and extreme variations in physical properties, there are convergence problems with the solution. According to Merkle, numerical results indicate that the level and gradient of absorptivity strongly affect convergence.

At this time, there is insufficient experimental evidence to support any of the theoretical models described. The models presented are primitive in that they contain too many simplifying assumptions or they are divergent in some regimes. It is important to develop a model without simplifying assumptions and to be able to obtain a complete solution in all regimes. It is then necessary to have experimental data to either verify or disqualify the theoretical formulation.
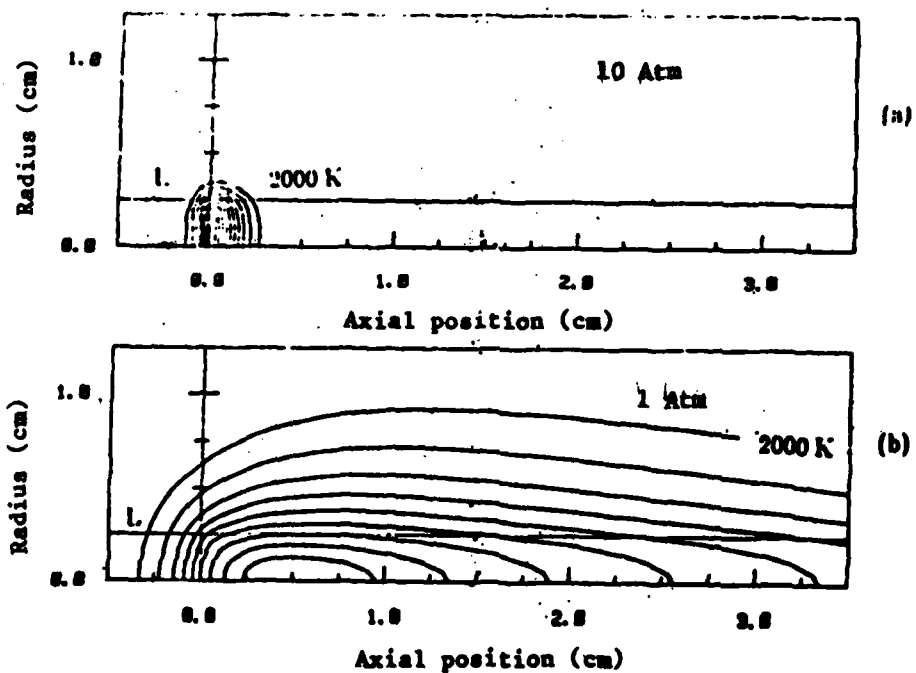
Figure A-5. **Keefer's Two-dimensional Temperature Profile.**
(Each Isotherm is an Increment of 2000 K.)

LASER ABSORPTION EXPERIMENTAL RESEARCH

In the past, there has been a large amount of analytical work done in the area of laser absorption for propulsion. In contrast, there has been insufficient experimental reseach to verify, disprove, or refine the theoretical work. This section presents some of the experimental research that has made a significant contribution to the field of beamed energy propulsion. The experimental research for laser propulsion is of interest because the experimental techniques and diagnostics used can be applied to solar thermal propulsion.

In a contract with AFRPL United Technologies Research Center (UTRC) performed experiments to measure temperature dependent absorption lengths of hydrogen–seedant mixtures to temperatures as high as $3700°K$ at ten atmospheres. A high pressure gas cell was used for containment with a high power CW CO_2 laser sustaining the plasma. The particular mixtures studied were H_2/H_2O, H_2/D_2O, and H_2/NH_3 at $10.6 \mu m$ wavelength radiation. The results here are not of particular interest, but the experimental approach is valuable.

The pressure cell depicted in Fig. A-6 was originally designed without the upper portion. In an early experiment, the zinc selinide window cracked because of excessive heating. Bouyancy driven convective heat flow caused high temperatures at the window and therefore failure. Moving the window away from the focal point (plasma station) reduced the heat loading and prevented damage.
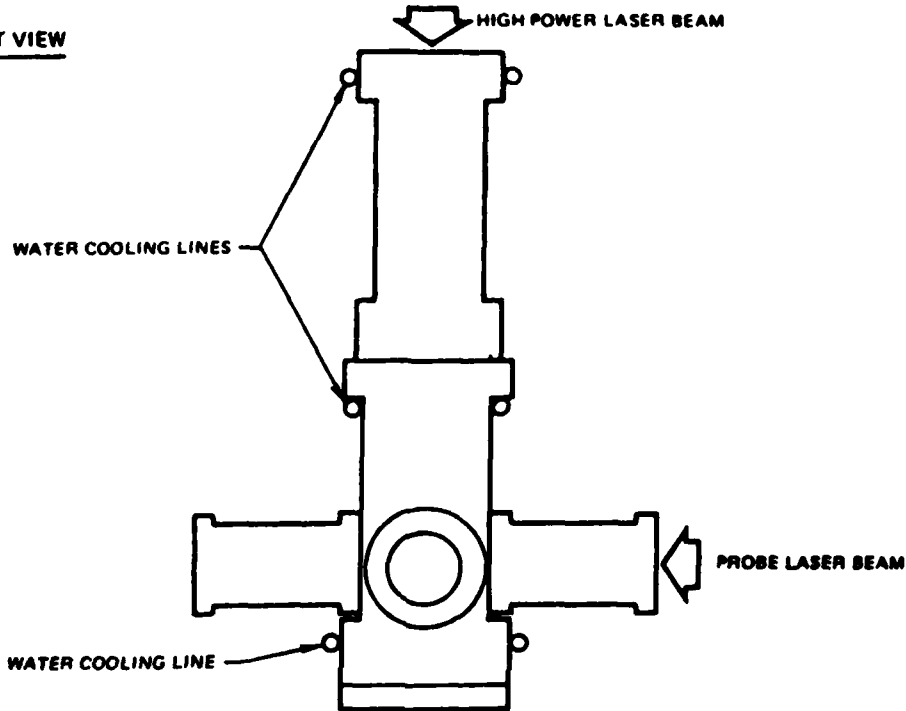
Four windowed ports to the pressure cell are shown in Fig. A-6. Two of the ports were used for transmission of the probe laser which measures gas properties. A third port was needed for the high power pulsed laser used for plasma ignition. The fourth window was used as a viewing port for beam alignment.

The high power CW laser beam was accurately focused at the center line intersection of the window ports. The pulsed laser beam was also focused at this point. With this intense radiation occurring at or near a single point,

HIGH PRESSURE PLASMA CONTAINMENT CELL

ONE INCH

FRONT VIEW

HIGH POWER LASER BEAM

WATER COOLING LINES

PROBE LASER BEAM

WATER COOLING LINE

SIDE VIEW

THERMOCOUPLE WELLS

GAS MIXTURE IN

GAS MIXTURE OUT
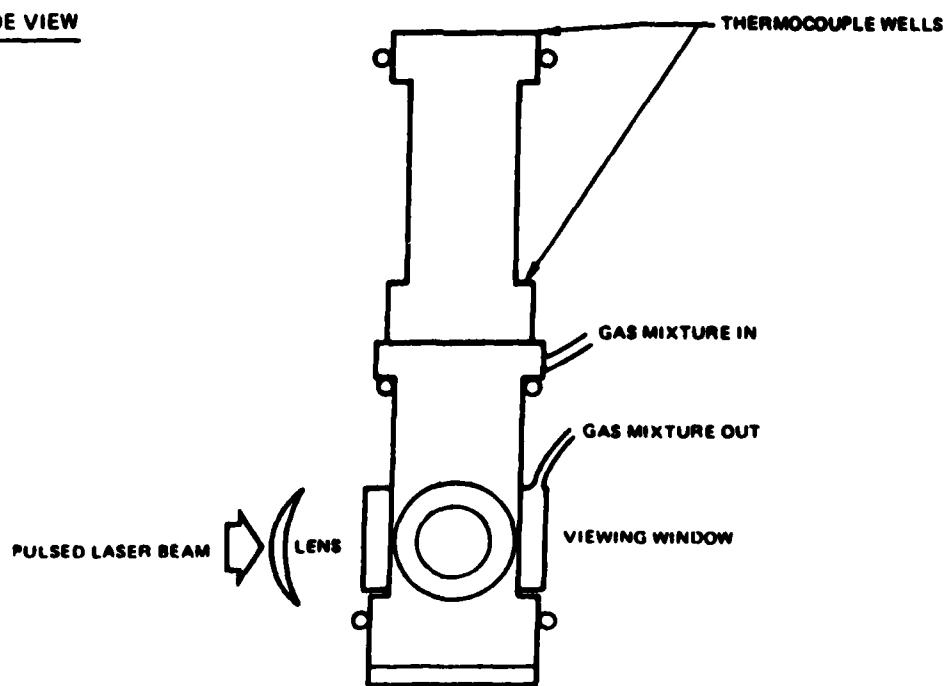
PULSED LASER BEAM

LENS

VIEWING WINDOW

Figure A-6. The UTRC High Pressure Gas Cell.

breakdown occurred easily with no difficulties in sustaining the plasma. There were no problems in sustaining the plasma down to pressures as low as 5 atmospheres as long as the initial cell temperature was near ambient. Regardless of pressure, a sustained plasma was not possible at high cell temperatures. A UTRC hypothesis for this phenomenon is that with higher temperatures, temperature gradients and therefore refractive index gradients of the window occurred causing difficulties in the focusing of the CO_2 laser beam. This would result in an intensity loss at the focal point where breakdown is desired.

The diagnostic equipment used in this experiment is shown in Fig. A-7. The objective of the system was to simultaneously determine the spatial dependence of power loss and optical phase shift of 10.6 m wavelength light as it passed through the absorbing gas. The absorption coefficient could then be determined from this information. The cell was placed in one arm of a Mach Zehnder interferometer with spatial mobility on the y axis.

A CO_2 laser was used as the light source. Two beam splitters and two shutters were used so that 4 intensity readings could be taken in a short time interval. Beam splitter 1 divided the beam so that 50 percent of the light passed through the cell and 50 percent was used as a reference. Beam splitter 2 brought these two beams together after passing the cell. The HeNe laser was used to ensure that the correct intensity comparisons were made for a given y position. As shown in the following table the two shutters were operated so the complete data set could be obtained by a pair of detectors.

Shutter 1	Shutter 2	Result
Open	Open	Interferometer throughput
Open	Closed	Cell throughput
Closed	Open	Reference throughput
Closed	Closed	Spontaneous Emission

Absorption coefficients were obtained from this system. Review by AFRPL
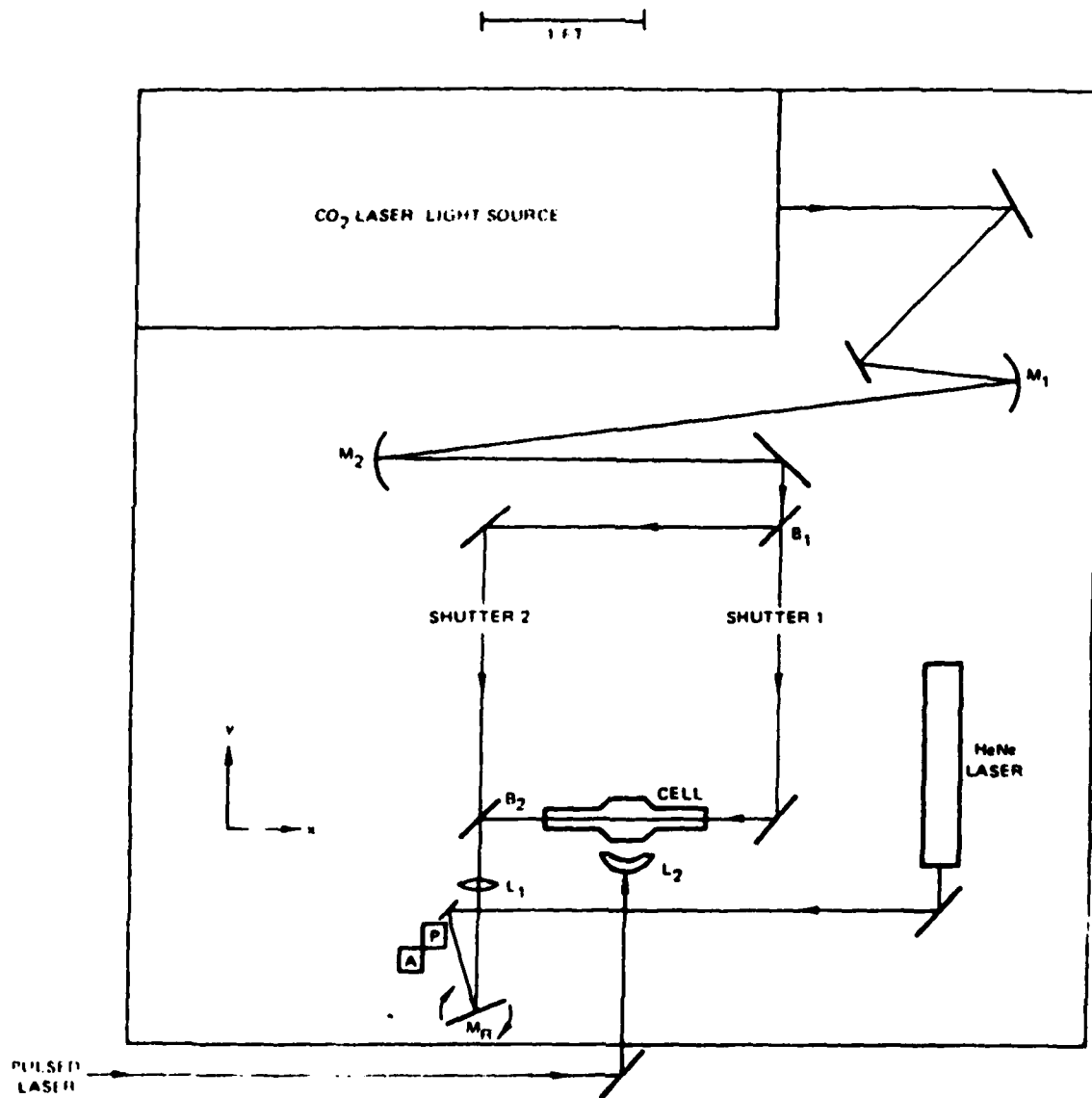
DIAGNOSTIC APPARATUS

Figure A-7. **Diagnostic Schematic for the UTRC Experiments.**

personnel found the results to be higher than predicted. Another contract to measure the absorption properties of the same mixtures was then given to PSI.

PSI used a shock tube to perform the absorption experiments. A shock tube can almost instantaneously take a gas mixture to a desired temperature given an initial pressure ratio (driver to driven pressure). The laser absorption test can then be made at these temperatures and pressures with test times up to a millisecond. The shock tube system used by PSI is shown in Fig. A-8.

The laser absorption test section was placed near the endwall of the shock tube. An inert gas was used as the driver gas and the seedant as the driven gas. A pressure transducer located at the same axial distance as the absorption region measured the pressure. A 10.6 μm CO_2 laser was used as the radiation source. The beam was split with 90 percent of the radiation passing through a salt (NaCl) diffuser to correct for refractive errors and then it was passed into the test section. The intensity of transmitted light was then measured by an Hg-Cd-Te detector located on the opposite side of the tube. The remaining 10 percent of the laser radiation was brought into a calibration cell to measure the exact wavelength of light. The absorption coefficient was then calculated using the optical transmission, the total pressure, and the path length. This test section is depicted in Fig. A-9.

In a joint follow-on study NASA Marshall and AFRPL have recently started another experimental program to measure laser absorption in water vapor.[8] This project is not complete with the fabrication of hardware presently taking place. The experimental apparatus is presented in Fig. A-10.
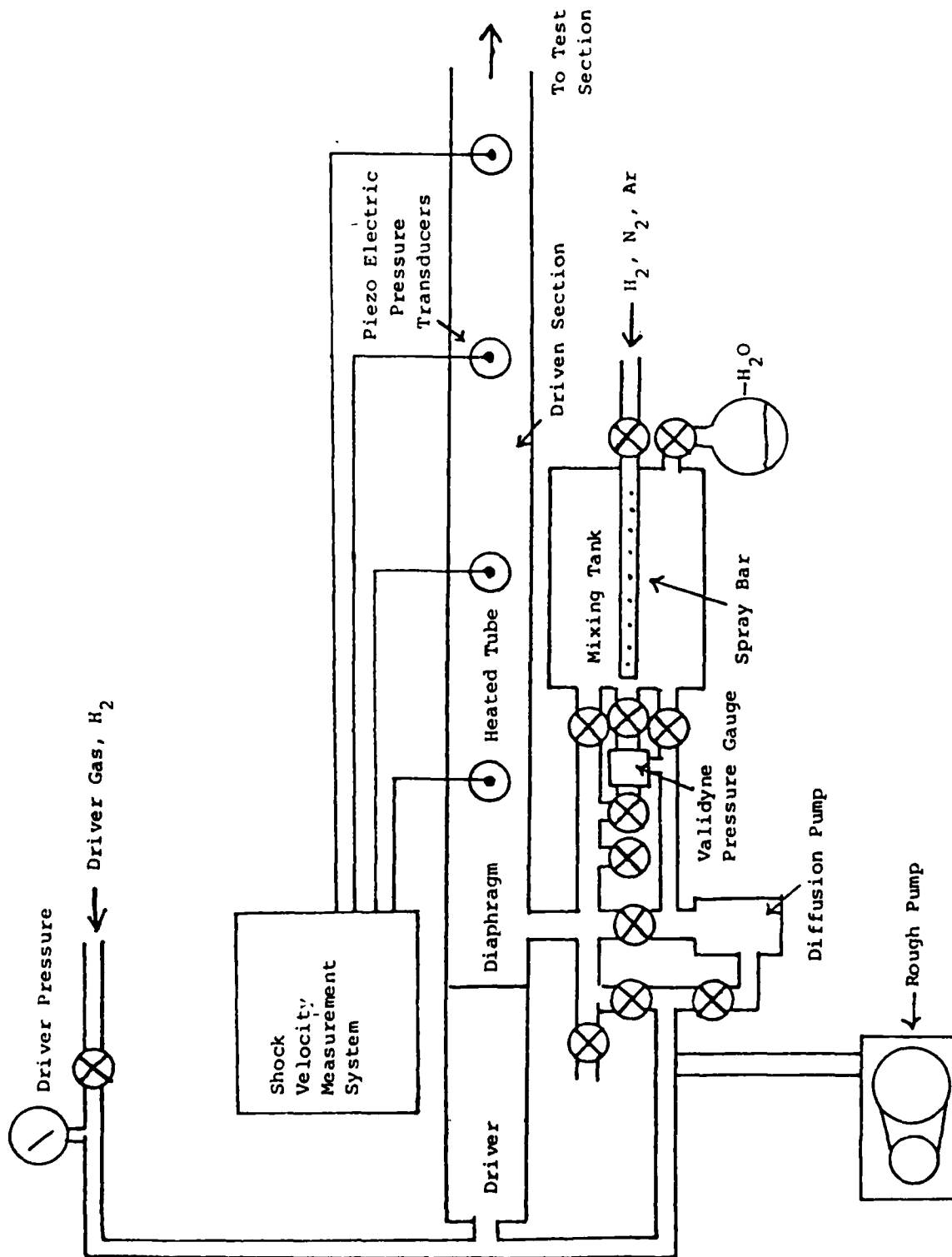
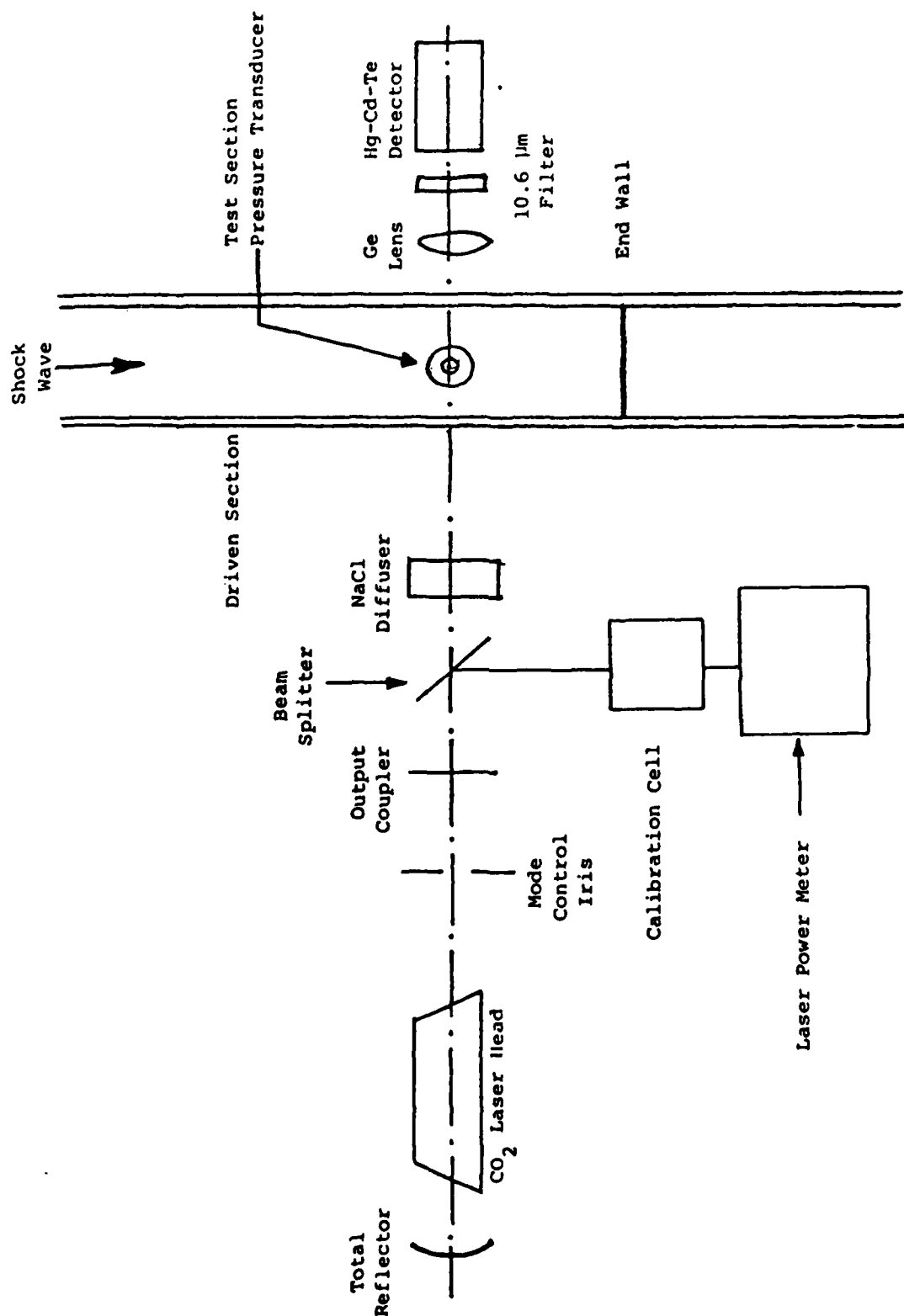Figure A-8. PSI's Shock Tube Experiment Gas Handling System.

Figure A-9. PSI's Shock Tube Experiment Test Section and Diagnostics.
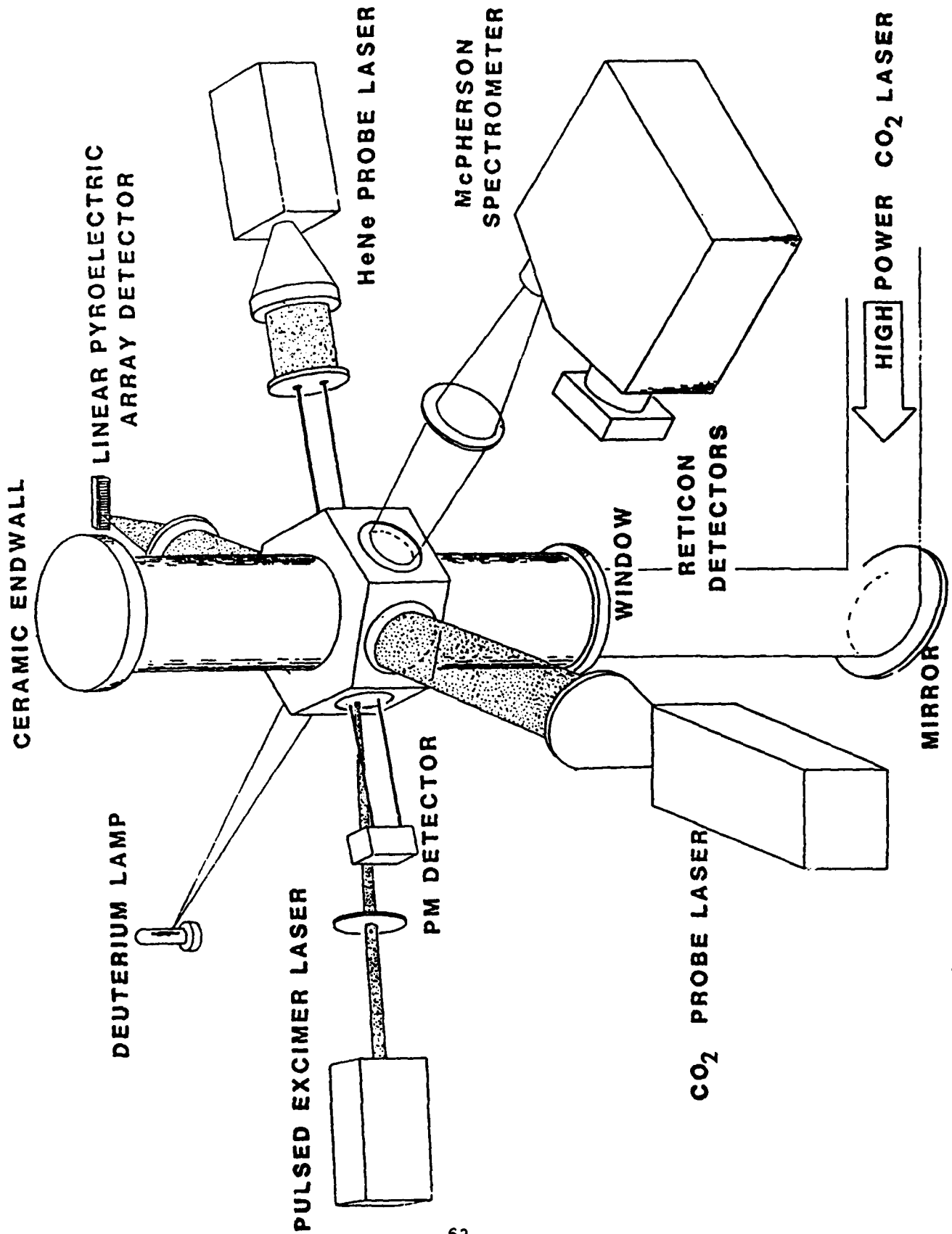
Figure A-10. _NASA Marshall/AFRPL Experimental Apparatus and Diagnostics._

LINEAR PYROELECTRIC ARRAY DETECTOR

HeNe PROBE LASER

McPHERSON SPECTROMETER

HIGH POWER CO₂ LASER

CERAMIC ENDWALL

WINDOW

RETICON DETECTORS

MIRROR

DEUTERIUM LAMP

PULSED EXCIMER LASER

PM DETECTOR

CO₂ PROBE LASER

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This approach is slightly different from the pressure cell or shock tube experiments. A high power CO_2 laser is used to generate a "thermal absorption wave" originating at the ceramic endwall. This is shown in Fig. A-11. The heating of the ceramic wall by the laser causes heating of the gas next to the wall. Conduction causes the wave to "move forward" while it continues to expand. This heating mechanism is used to obtain temperatures suitable for absorption measurements.

The diagnostics to be used in this experiment are much more extensive than those used previously. Temperature will be measured by two methods. First, a McPherson spectrometer will be used to find the temperature in addition to the spectral output of the mixture. Second, temperature will be derived from the speed of sound. A pulsed eximer laser will be used to generate a wave with a HeNe probe laser measuring the velocity of the wave. The temperature will then be calculated from this velocity:

$$T = a^2 / \gamma g_c R$$

where

R   = gas constant;

g_c = gravitational constant;

γ = specific heat ratio; and

a   = measured velocity.

A CO_2 probe laser will be used as the radiation source with a spiricon detector array measuring the intensity output from the gas.

LASER SUPPORTED THERMAL WAVE
2 ATM H2O, 8 ATM H2

I0= 375 W/CM^2
TIME INC. =4 SECS
X AXIS = CM

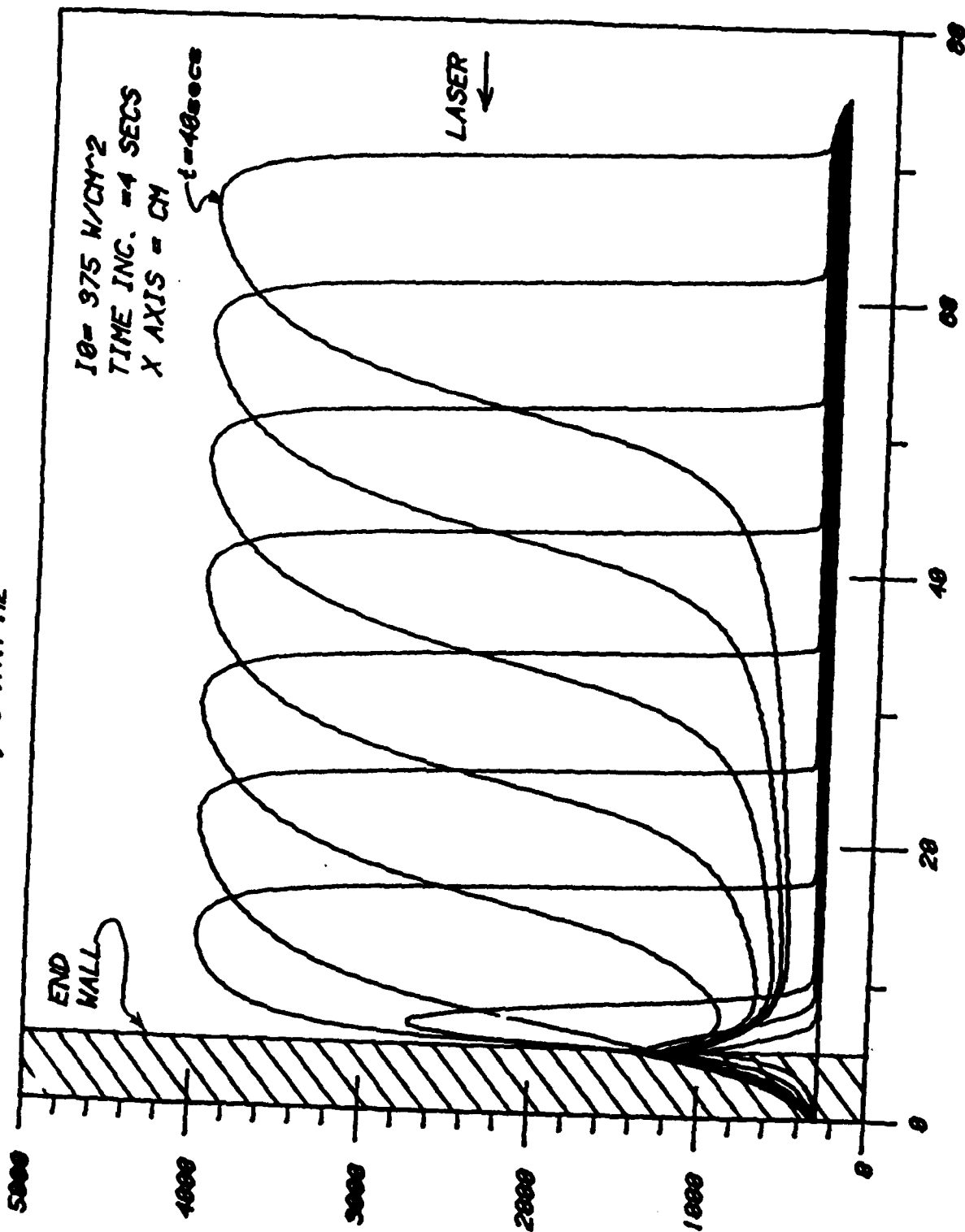t=48 secs

LASER

END WALL

DEGREES KELVIN

Figure A-11. Depiction of Thermal Absorption Wave.

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This approach appears to be a very accurate method of measuring absorption coefficients. Again, this work is incomplete with results soon to follow. According to Dr Dennis Keefer, this method can be used to measure absorption coefficients of hydrogen-alkali mixtures. A closer look at this concept will be made when the results from this research are known.

Perhaps more notable research was accomplished by Avco Everett Research Labs (AERL) under a contract with NASA Lewis Research Center.[9] The purpose of this research was to evaluate laser absorption in flowing media. In this case an actual laser rocket thruster was designed, fabricated and tested.

The laser thruster is shown in Fig. A-12. A CW CO_2 welding laser was chosen as the radiation source capable of delivering power in excess of 10 kW. The laser radiation entered the thruster through a 1 millimeter diameter diamond window located at the end of an isolation tube. The purpose of the isolation tube was to prevent the seedant or hot gases from coming in contact with the diamond window. It should be mentioned that a diamond window is not practical for an actual thruster. The diameter of the window would necessarily increase with a power increase. Diamond windows of this size would be much too expensive.

The propellants used in this experiment were hydrogen, nitrogen, and helium, each pure or seeded with cesium. The primary absorption mechanism was electron-ion inverse Brehmsstrahlung. Unseeded gas was injected from a manifold near the diamond window so that the gas was flown across the window to keep it clean and cool. The cesium seed was then added further downstream. Cold gas flowing over a molten bath of cesium produced an aerosol of cesium particles.
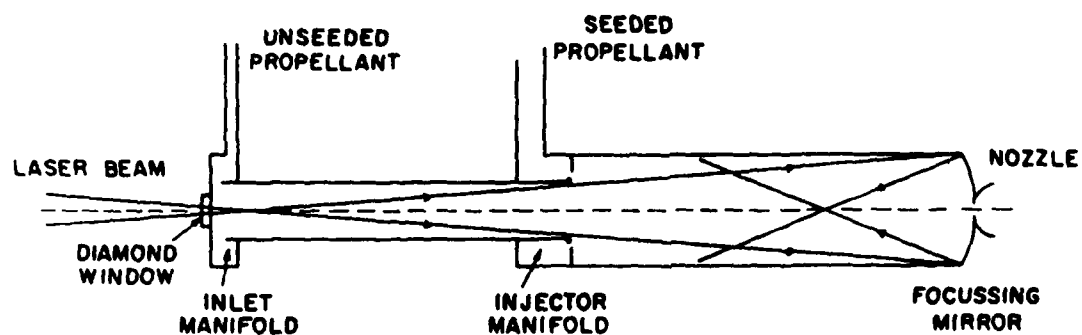
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Figure A-12. AERL's Laser Absorber Thruster.

The engine design in Fig. A-12 was chosen over other designs because of the accessibility of the nozzle and mirror. With the cesium seed, it was necessary to place the thruster in a sealed tank to avoid cesium contamination of the environment. While it was not expected that the cesium would damage the mirror, it was expected that cleaning of the mirror would be required often. Operation in the welding facility was very expensive ($125/hr) thus installation, cleaning and repairs needed to be accomplished in the shortest time possible. This design was chosen because the nozzle could be reached through a gloved port in the chamber with one hand. The nozzle could easily be removed and the mirror cleaned in a short time without exposing the thruster to the atmosphere.

Three testing sequences were conducted. The final test was made when the third and last diamond window popped. The first test sequence was made with unseeded propellants only. No breakdown occured regardless of laser power. The second and third test sequences included the cesium seed in many of the runs. Bright yellow flashes in the chamber and sparks flowing out the nozzle were observed in some cases (See Fig. A-13). This phenomenon could not be produced when the laser power fell below 10 kW. Runs with power levels of 15 kW were made but only for short durations because the high power caused severe degradation of the diamond window. Plasma ignition occurred when the yellow flash was observed and the vaporization of seed in the nozzle produced the yellow sparks.

Diagnostics in this experiment were not as extensive. An HeNe laser was used for system alignment. Two window ports were provided for viewing and photography. No other nonintrusive diagnostics were used.

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Figure A-13. <u>AERL's Thruster.</u>
Ionizing Cesium Can Be Seen Exiting the Nozzle.

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The most significant outcome from this research is that the concept of a beamed energy propulsion device was proven. Actual breakdown and plasma ignition was observed in this thruster. It is also important to note that these results were reproduced in many runs. According to Chapman and Otis, there is no reason to doubt the feasibility of the design approach. With this precedent set, there is now sufficient reason to advance the technology so that larger thrusters using laser and solar energy as an energy source may be designed.

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